

Computational Physics for Space Flight Applications

Presented by:
Robert A. Reed

NASA/GSFC Code 561
Greenbelt MD, 20771
robert.reed@nasa.gov

Supported in Part by:

- NASA Electronics Parts and Packaging (NEPP) Program
- Defense Threat Reduction Agency (DTRA)
- NASA Space Environment and Effects (SEE) Program
- NASA's James Webb Space Telescope (JWST)

Outline

- **Introduction to space radiation effects in microelectronics**
- **Using applied physics to help NASA meet mission objectives**
- **Example of applied computational physics**
 - James Webb Space Telescope
 - Single Event Effects in emerging microelectronic technologies
- **Future directions in applied computation physics**

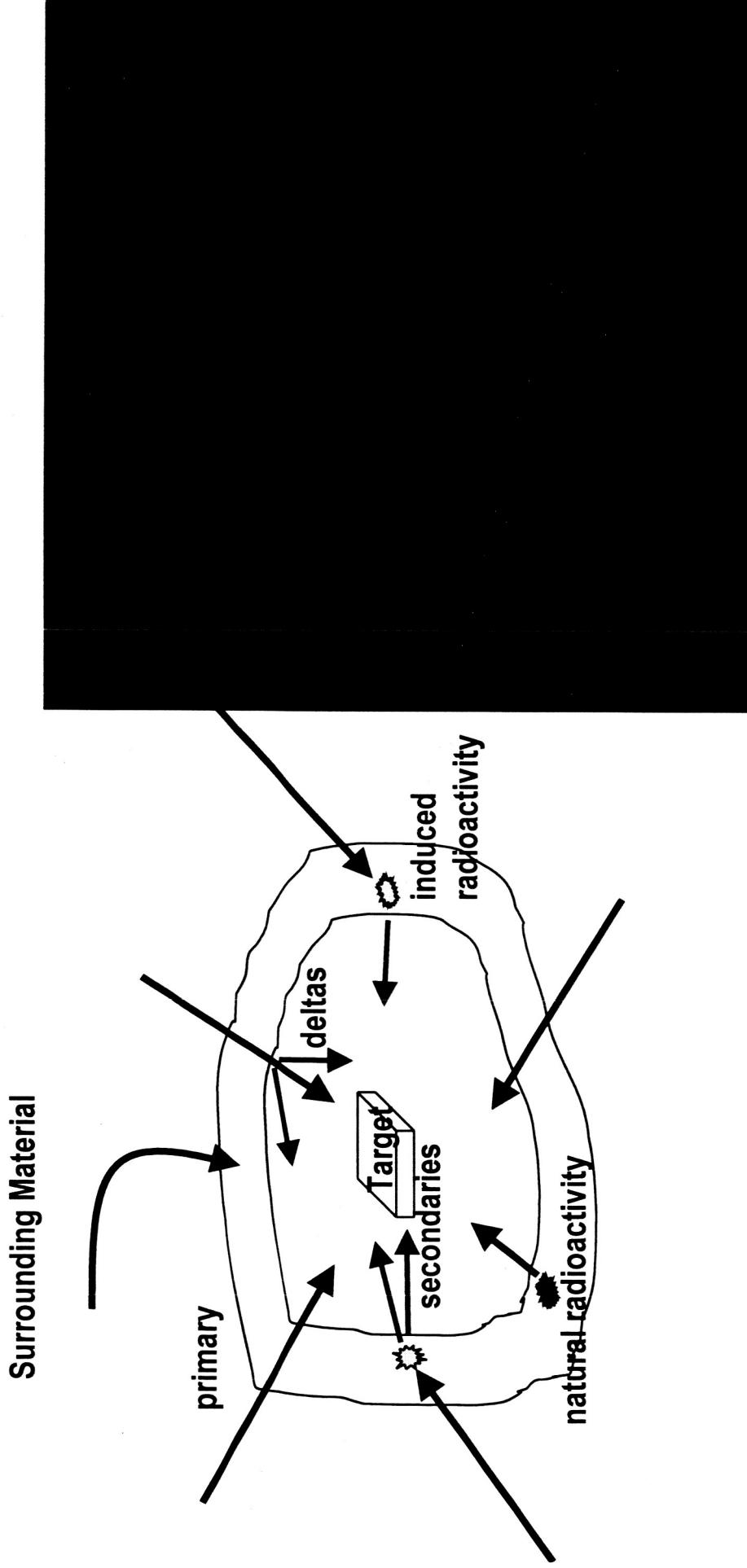
Space Radiation Environment

Three portions of the natural space environment contribute to the space environment effects hazard

- Solar particles
 - Protons and heavier ions
- Galactic Cosmic Rays (GCR)
 - For earth-orbiting craft, the earth's magnetic field provide some protection for GCR
- Trapped particles (in the belts)
- Hazard observed is a function of orbit and timeframe
- Environment is dynamic, models are static

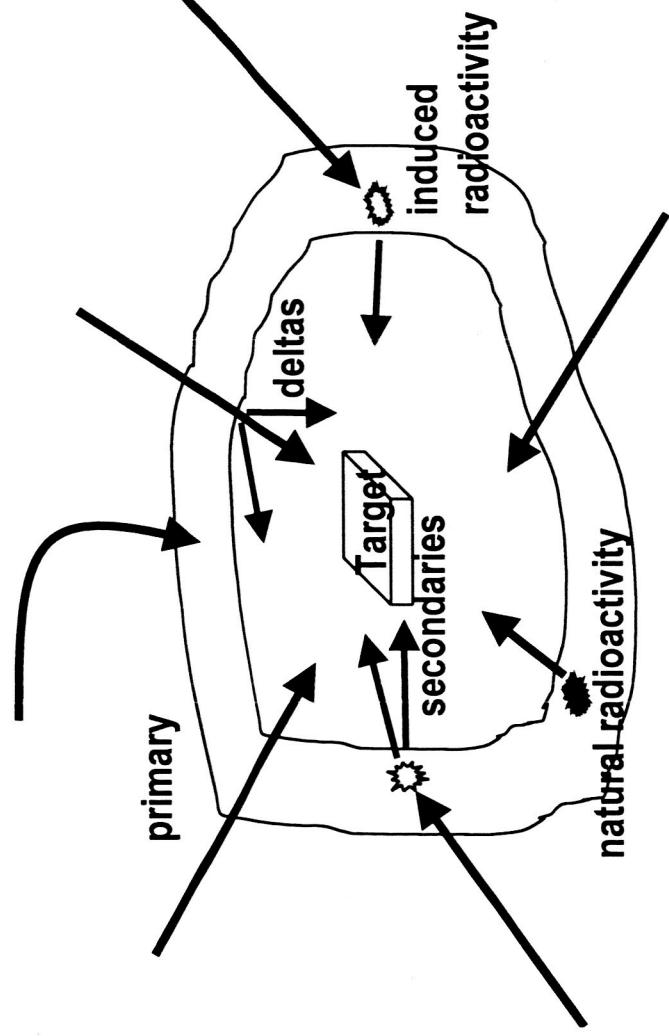


Modeling the Interaction of the Space Radiation Environment with the Spacecraft and Targets



Modeling the Interaction of the Space Radiation Environment with the Spacecraft and Targets

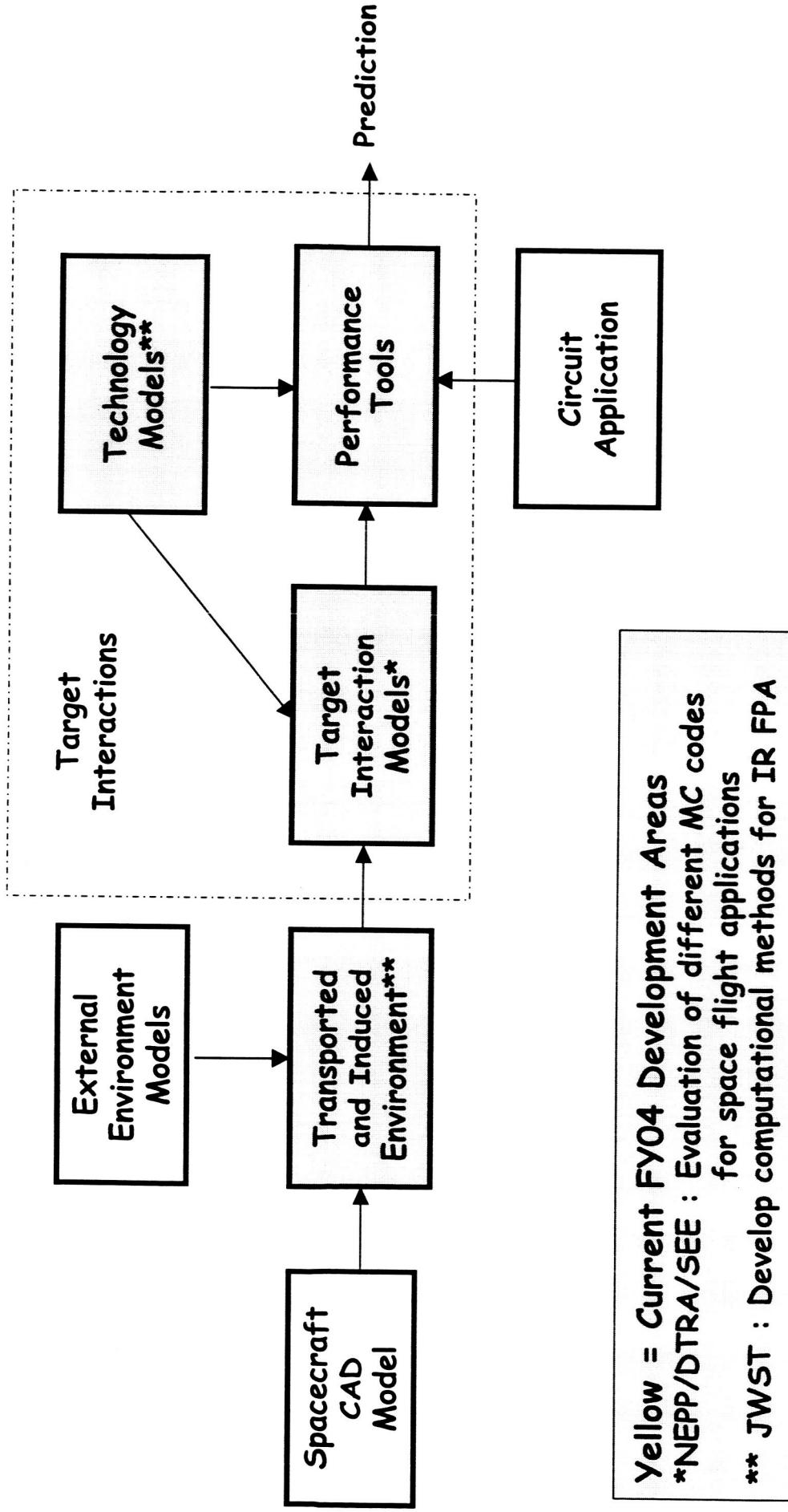
Surrounding Material



Monte Carlo Based Computation Physics Tools Currently Used at NASA/GSFC

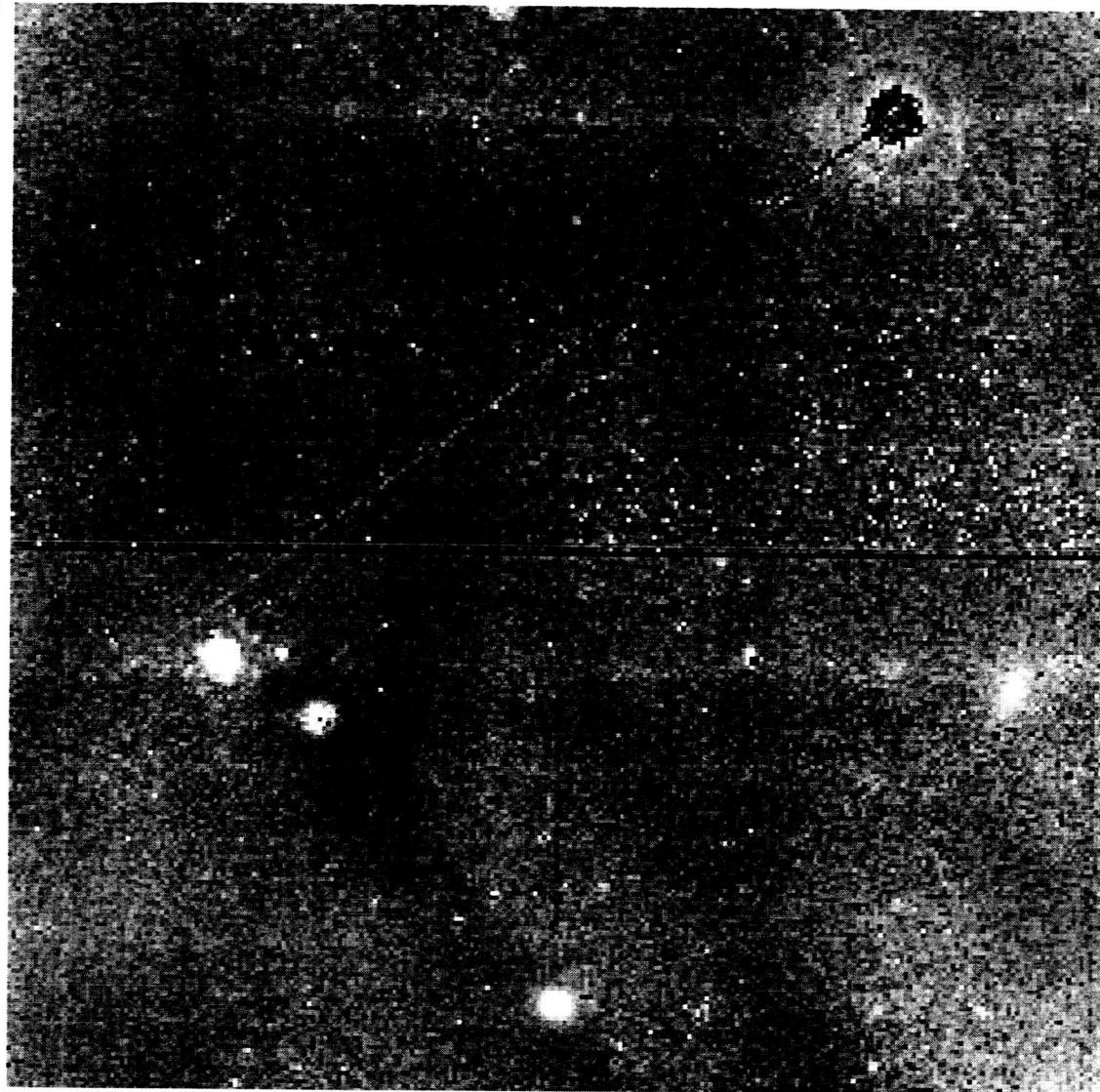
- GEANT4
 - A multi-national team of physicists and engineers are developing *Geant4* for the express purpose to Monte Carlo simulation of the passage of particles through matter.
 - Its application areas include high-energy physics and nuclear experiments, medical, accelerator and space physics studies.
- EMPC Inc.'s (a private company) NOVICE code suite
 - Developed to be a user-friendly, engineering tool for use, in part, by the space radiation effects community.
 - Its developer is highly regarded as an expert in radiation transport by the space radiation effects community.
- The Los Alamos National Laboratory's Monte Carlo N-Particle extended (MCNPX)
 - A general-purpose computer code that can be used for particle transport through materials.
 - Its application areas are similar to *Geant4*.
- NASA's Radiation Effects Array Charge Transport (REACT)
 - Simulation of charge transport through a semiconductor
 - Quasi-device physics (QDeP) code
- Clemson University Proton Interaction in Devices (CUPID)
 - Simulation of proton spallation reactions in Silicon
 - Tracks energy deposited in a right Rectangular Parallelepiped (RPP) volume

Space Computational Radiation Interaction Performance Tools (SCRIPT)



Space Radiation Interactions as Observed by NICMOS

Figure 2.4



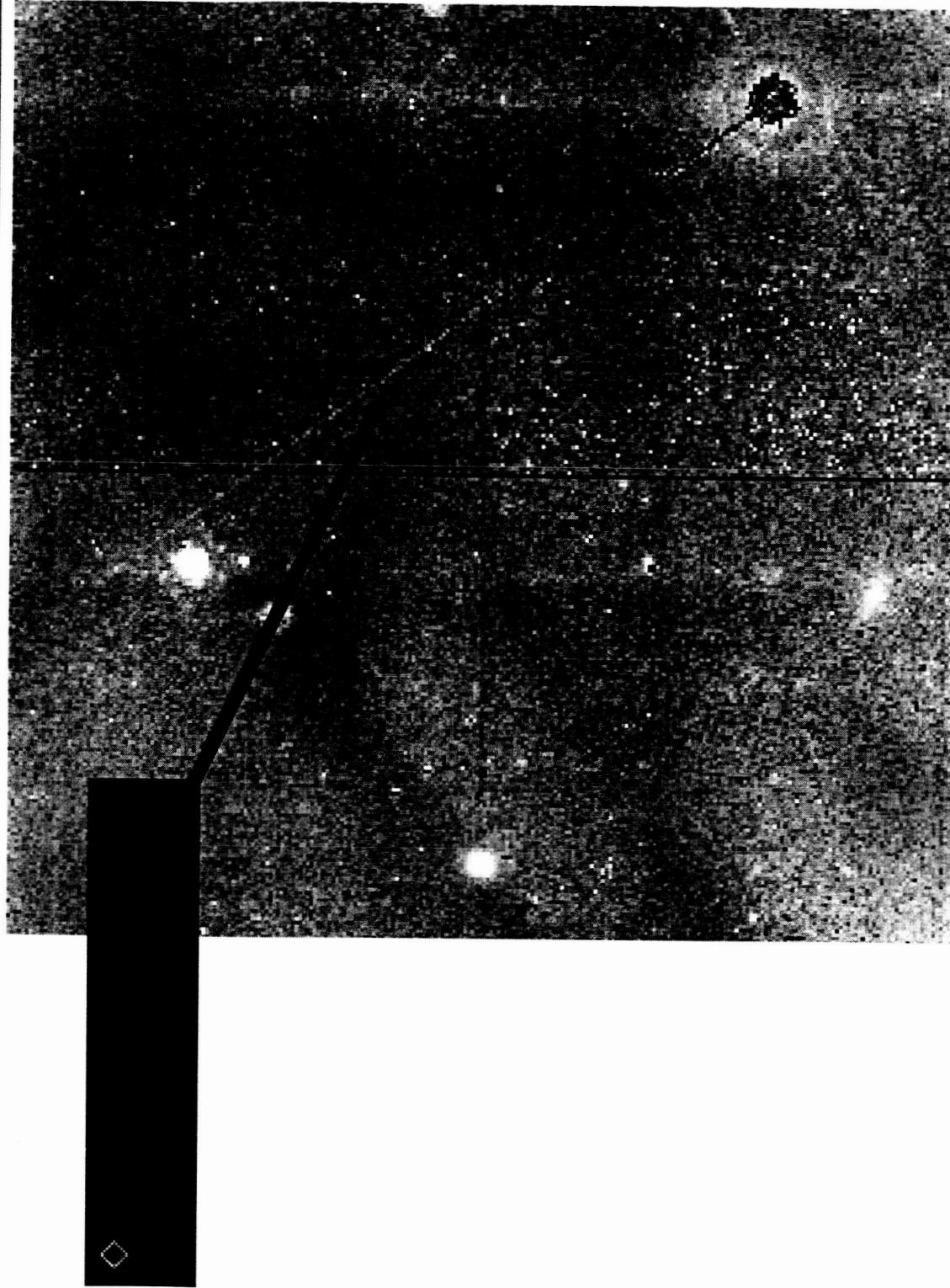
May 11 2004

<http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html>

Presented by Robert Reed, NASA/GSFC at Vanderbilt University

Space Radiation Interactions as Observed by NICMOS

Figure 2.4



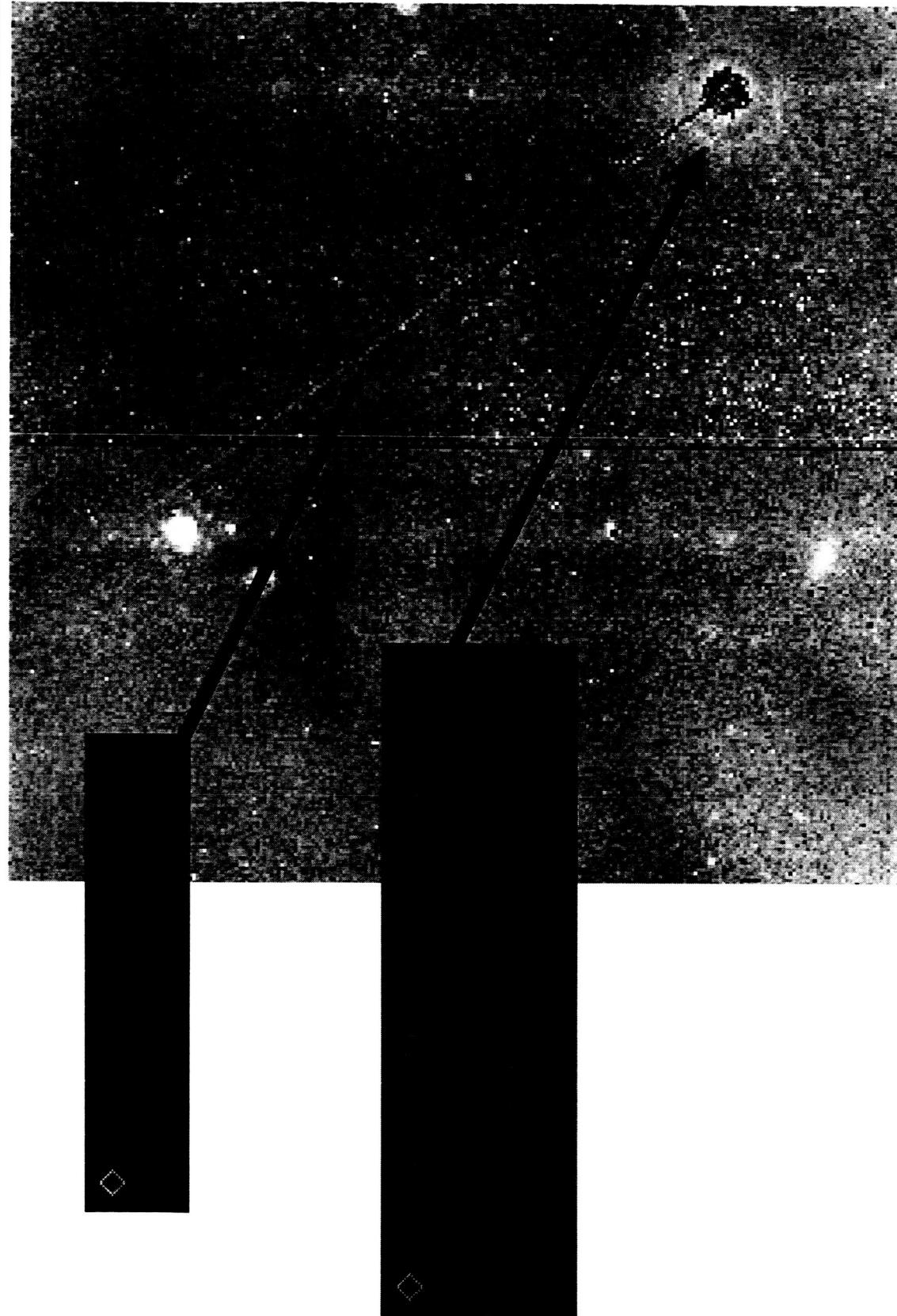
May, 11 2004

<http://www.stsci.edu/hst/nicmos/performanc/anomalies/bigcr.html>

Presented by Robert Reed, NASA/GSFC at Vanderbilt University

Space Radiation Interactions as Observed by NICMOS

Figure 2.4



May 11 2004

<http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html>

Presented by Robert Reed, NASA/GSFC at Vanderbilt University

Prompt Ionizing Events

Single Event Effects (SEE)

Figure 2.4

Prompt Ionizing Events

Figure 2.4

Single Event Effects (SEE)

- Direct Ionization

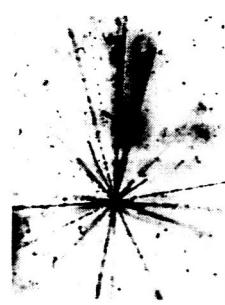
- Typically Heavier Ions ($Z>1$)
- Linear Energy Transfer (LET)
- Energy per length
- Frequency of the Events in space
- radiation



Direct

- Indirect Ionization

- Fragments from Nuclear Collision
- Proton Energy
- Frequency of the Events in space
- radiation



Indirect

P.J. McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course

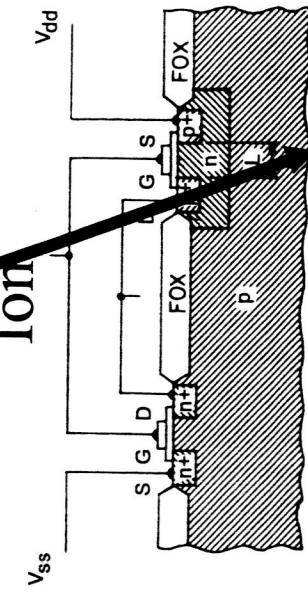
Prompt Ionizing Events

Figure 2.4

Single Event Effects (SEE)

Direct Ionization

- Typically Heavier Ions ($Z > 1$)
- Linear Energy Transfer (LET)
 - Energy per length
- Frequency of the Events in space radiation



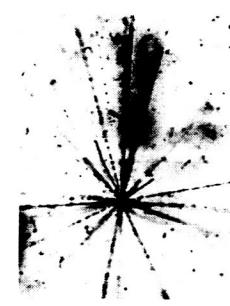
Indirect Ionization

- Fragments from Nuclear Collision
- Proton Energy
- Frequency of the Events in space radiation



Charge collected on a sensitive node in an electrical circuit causing an unwanted change in information stored on the component

- Single Event Upset
- Single Event Latchup
- Single Event Transient
- Single Event Gate Rupture
- Single Event Functional Interrupt
- Single Event ...



Indirect

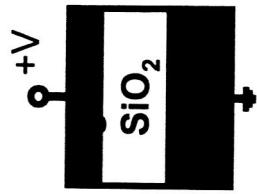
P.J. McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course

Cumulative Degradation for Multiple Ionizing Events

Figure 2.5

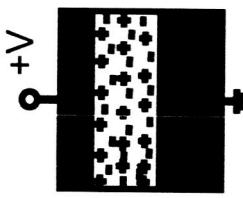
Total Ionizing Dose (TID)

BEFORE IRRADIATION

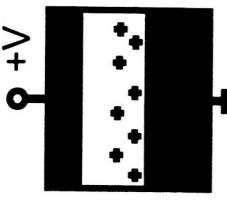


- Permanent damage, some annealing occurs for certain devices
- Can lead to Functional failure

DURING IRRADIATION



DURING AND AFTER IRRADIATION



IONIZATION AND RECOMBINATION

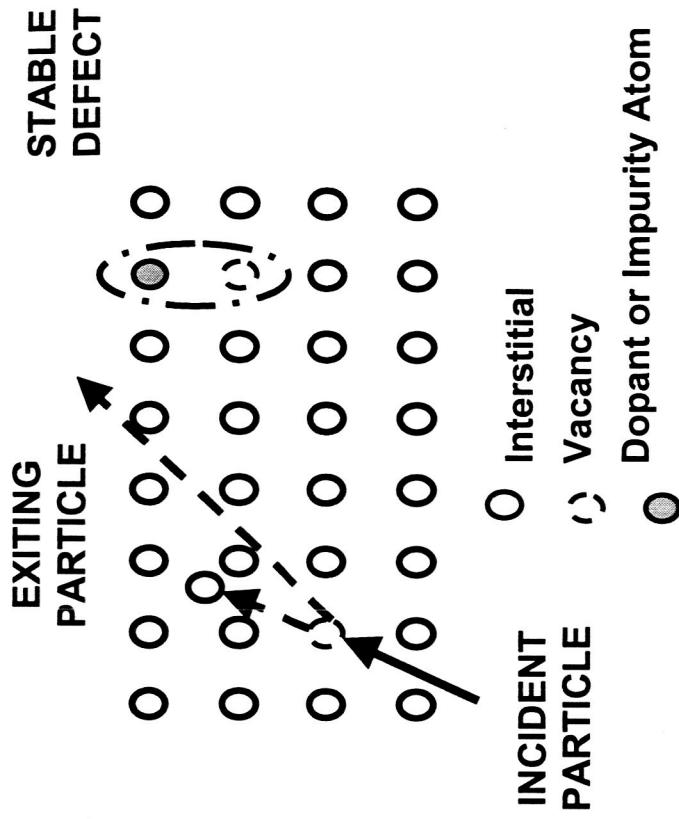
DRIFT, DIFFUSION AND TRAPPING

J.L. Leray, Notes from 1999 IEEE Nuclear and Space Radiation Effects Conference Short Course

Cumulative Degradation and Prompt Response for Non-Ionizing Events

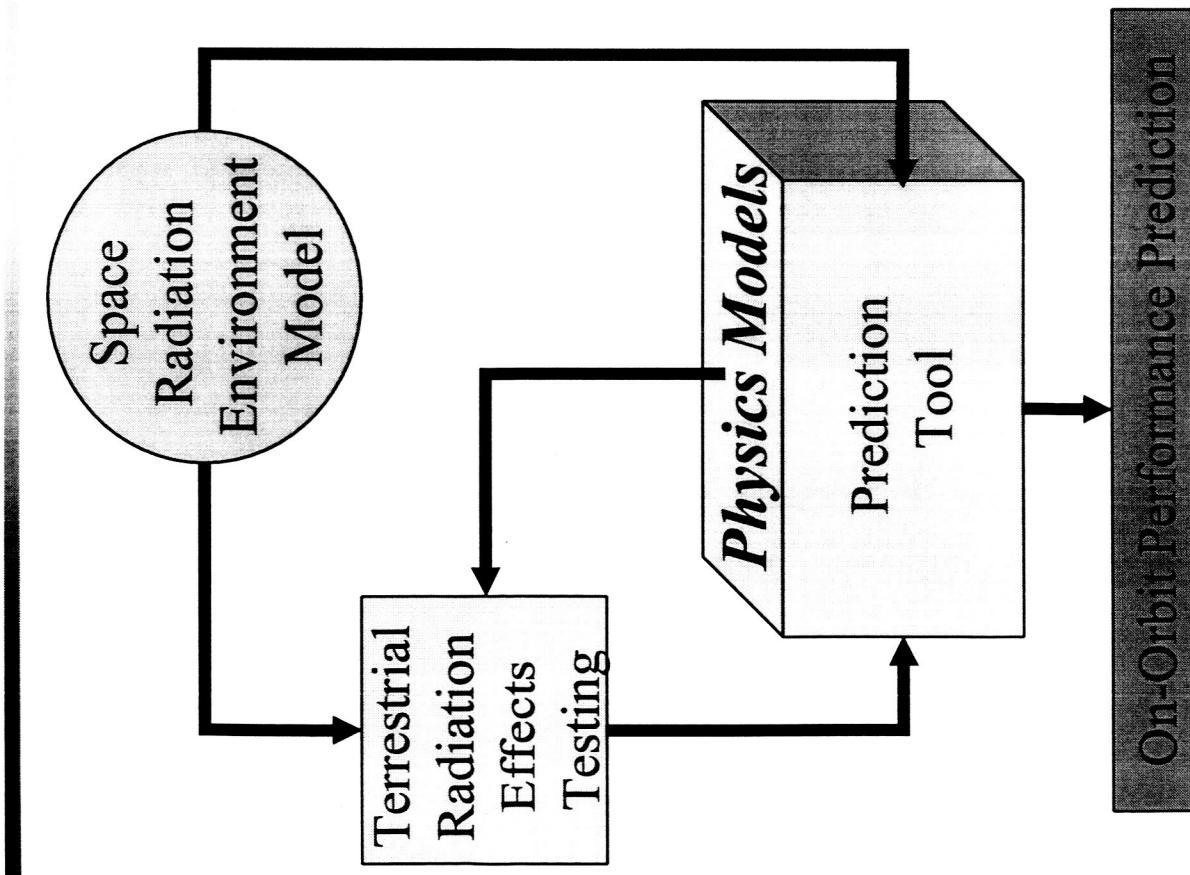
Displacement Damage

- Cumulative effects that cause device performance degradation
 - Displacement Damage Dose
 - Prompt effects causing device performance degradation
- Permanent damage, some annealing occurs for certain devices



P.W. Marshall and C.J. Marshall, Notes from 1999 IEEE Nuclear and Space Radiation Effects Conference Short Course

General On-Orbit Performance Prediction

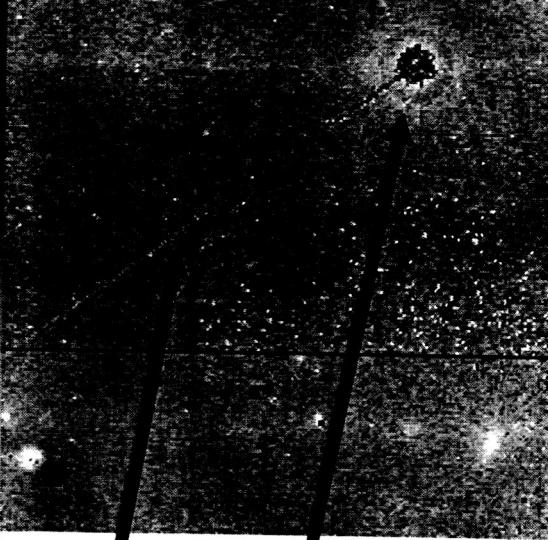


- The details of each step in this process depend on the type effect that is being analyzed
 - e.g. prompt response (SEE) will be different than cumulative degradation (TTID)

Applications of Computation Physics

Figure 2.4

- **Atomic Interactions**
 - Direct Ionization
 - TID
 - SEE
- **Interaction with Nucleus**
 - Indirect Ionization
 - Nucleus is Displaced
 - SEE
 - Displacement Damage



Computational Radiation Transport and Interaction Physics (CRTIP)

- NOVICE is the best suited for TID studies*
 - Adjoint mode monte-carlo
- MCNPX is the best suited for displacement damage studies*
 - Uses Lindhard energy partitioning
 - Includes elastic scattering
- GEANT4 is the suited for SEE studies*
 - Most flexible for user modules
- REACT is the suited for SEE studies*
 - Quasi-device physics code

* These results will change as we review other codes and as these codes improve

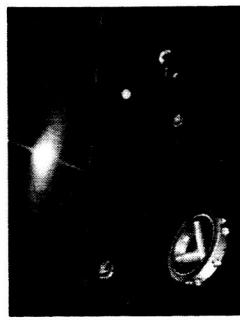
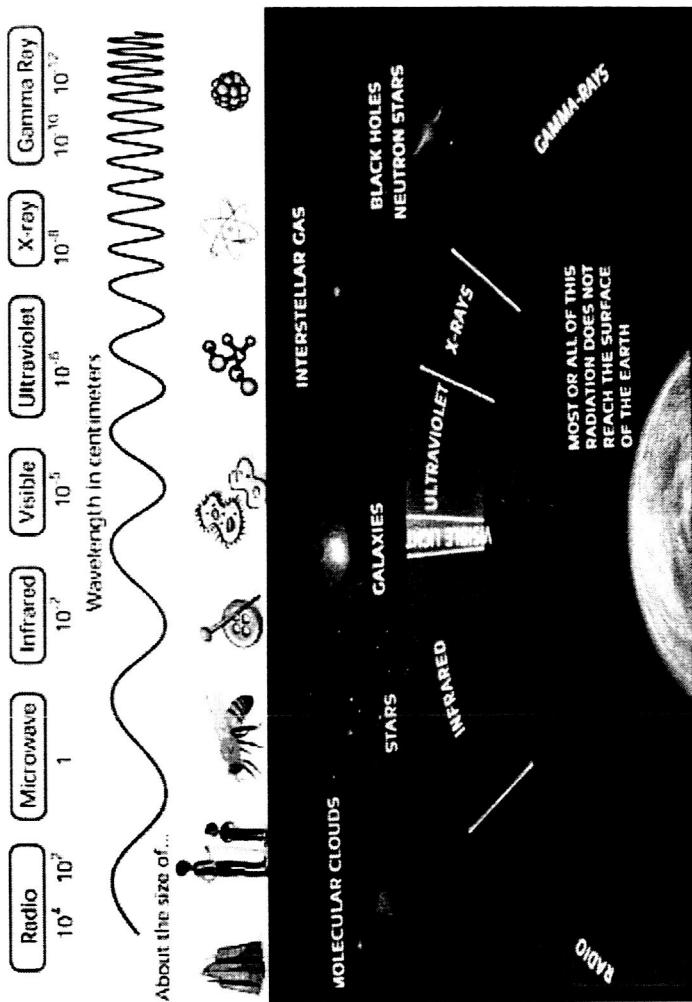


Computational Radiation Transport and Interaction Physics

James Webb Space Telescope

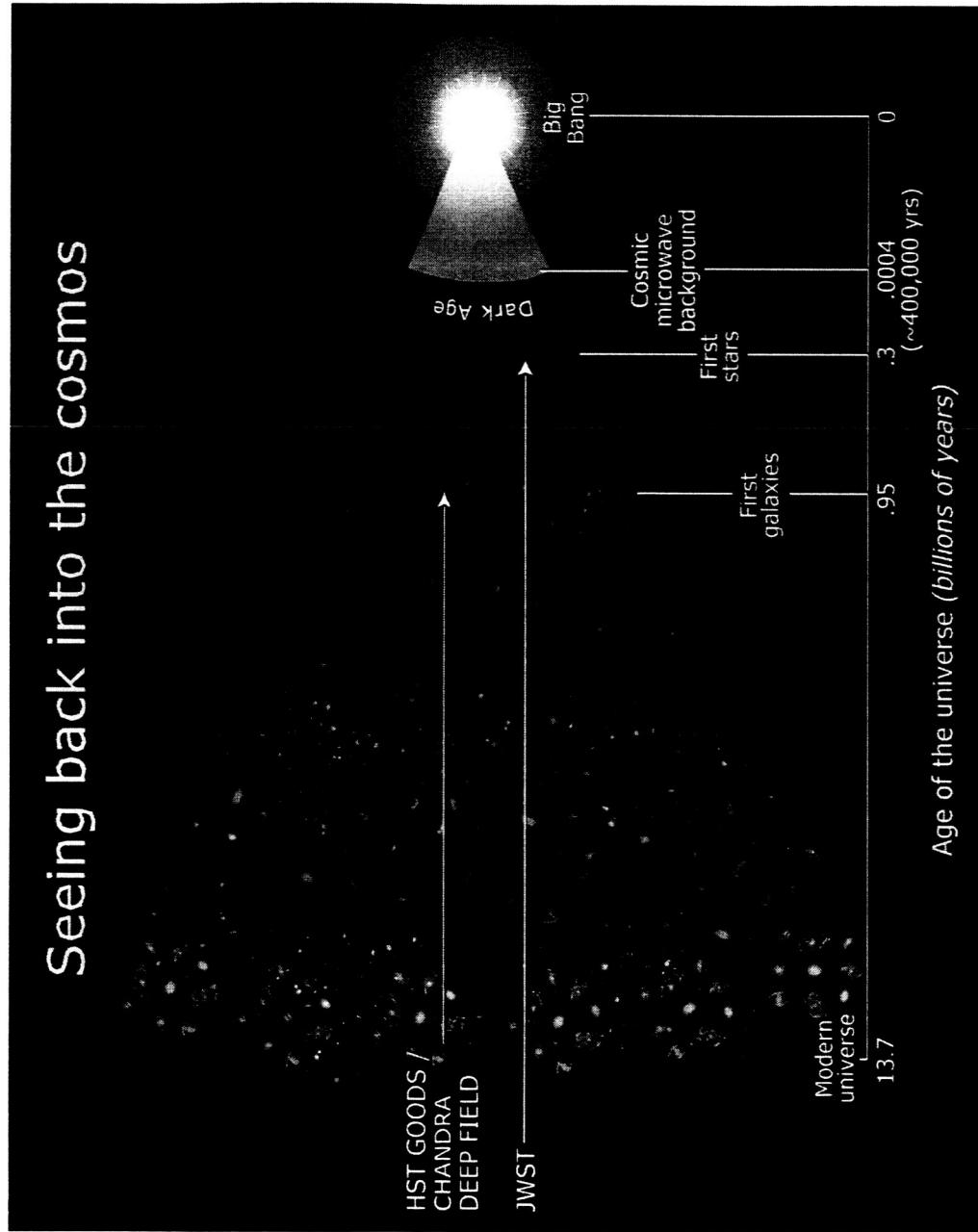
Low Noise Quantitative Detection Across the Spectrum

- **Ground-based Radio Astronomy**
- **Microwave looks at the Cosmic Microwave Background**
 - COBE, FIRS, WMAP
- **Mid to long wave IR (>5 mm)**
 - SIRTF, JWST
- **Near Infrared**
 - HST - WFC3 & NICMOS
 - HST - WFC2, ACS, WFC3
- **Visible (panchromatic)**
 - HST - WFC2, ACS, WFC3
- **Near uV to VUV (solar phys)**
 - SOHO, SDO, STEREO
- **x-ray**
 - CHANDRA, XMM-Newton
 - GRO, GLAST, RHESSI
- **Gravity wave - Laser Interferometer Space Antenna - LISA**

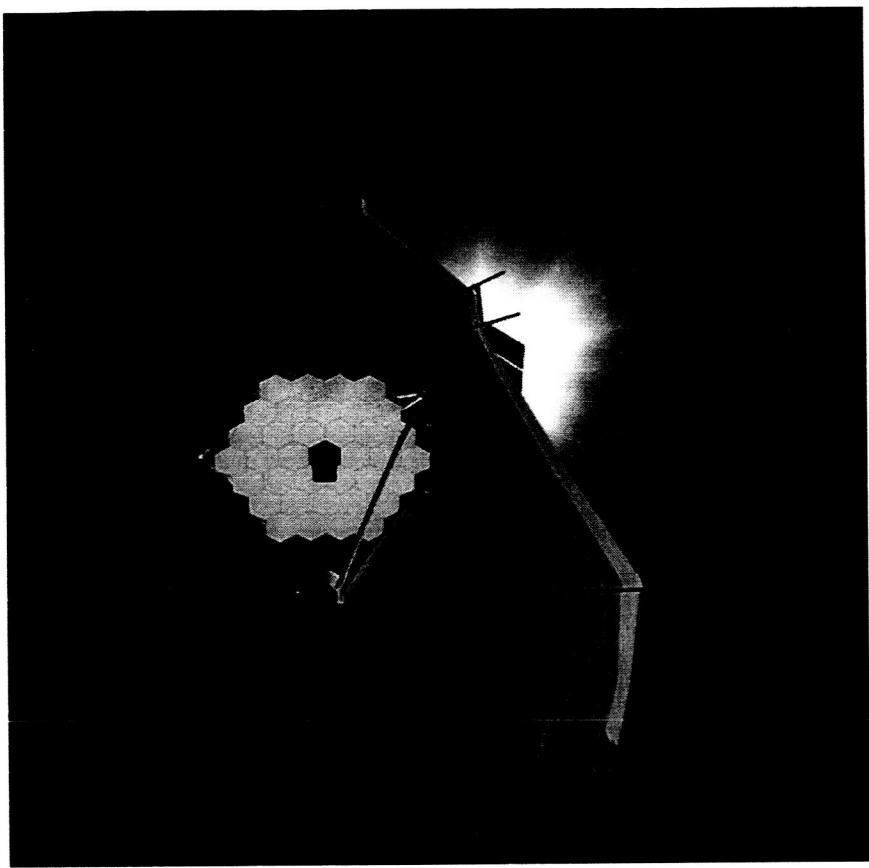
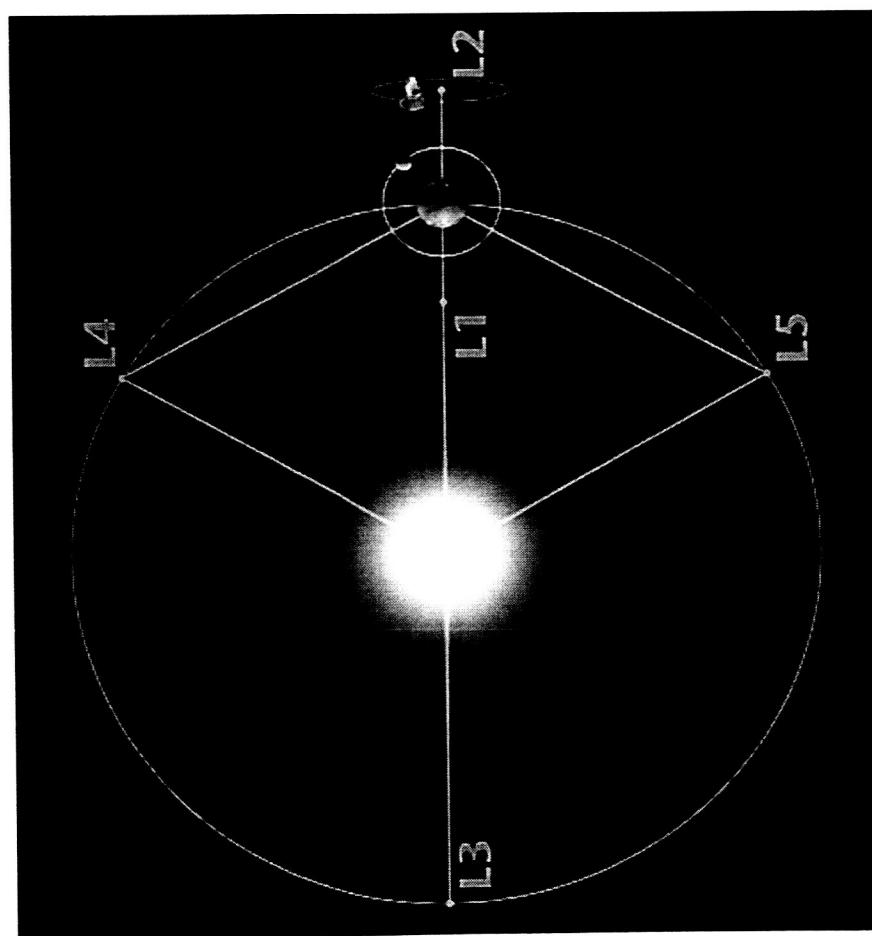


James Webb Space Telescope

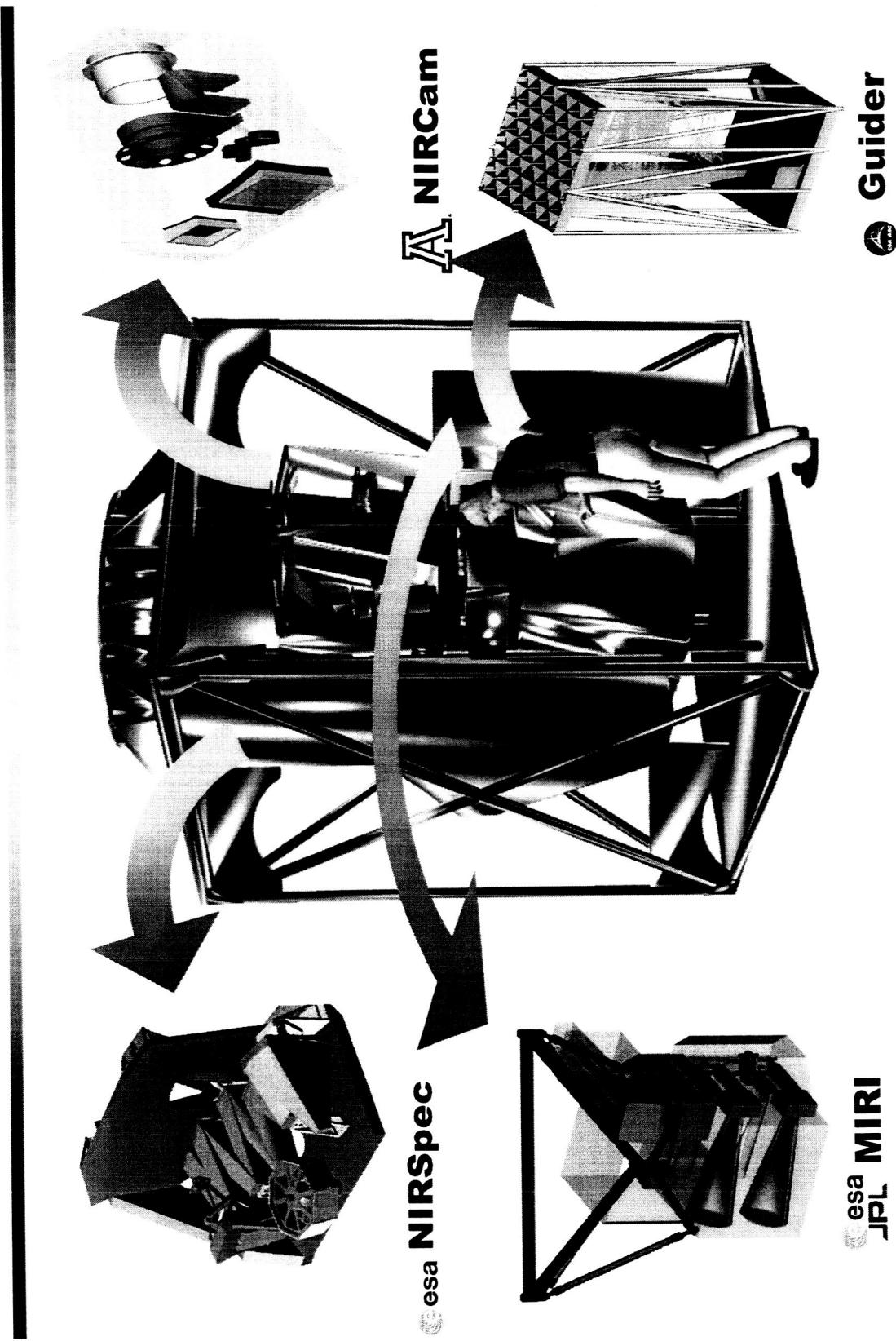
Seeing back into the cosmos



James Webb Space Telescope



James Webb Space Telescope



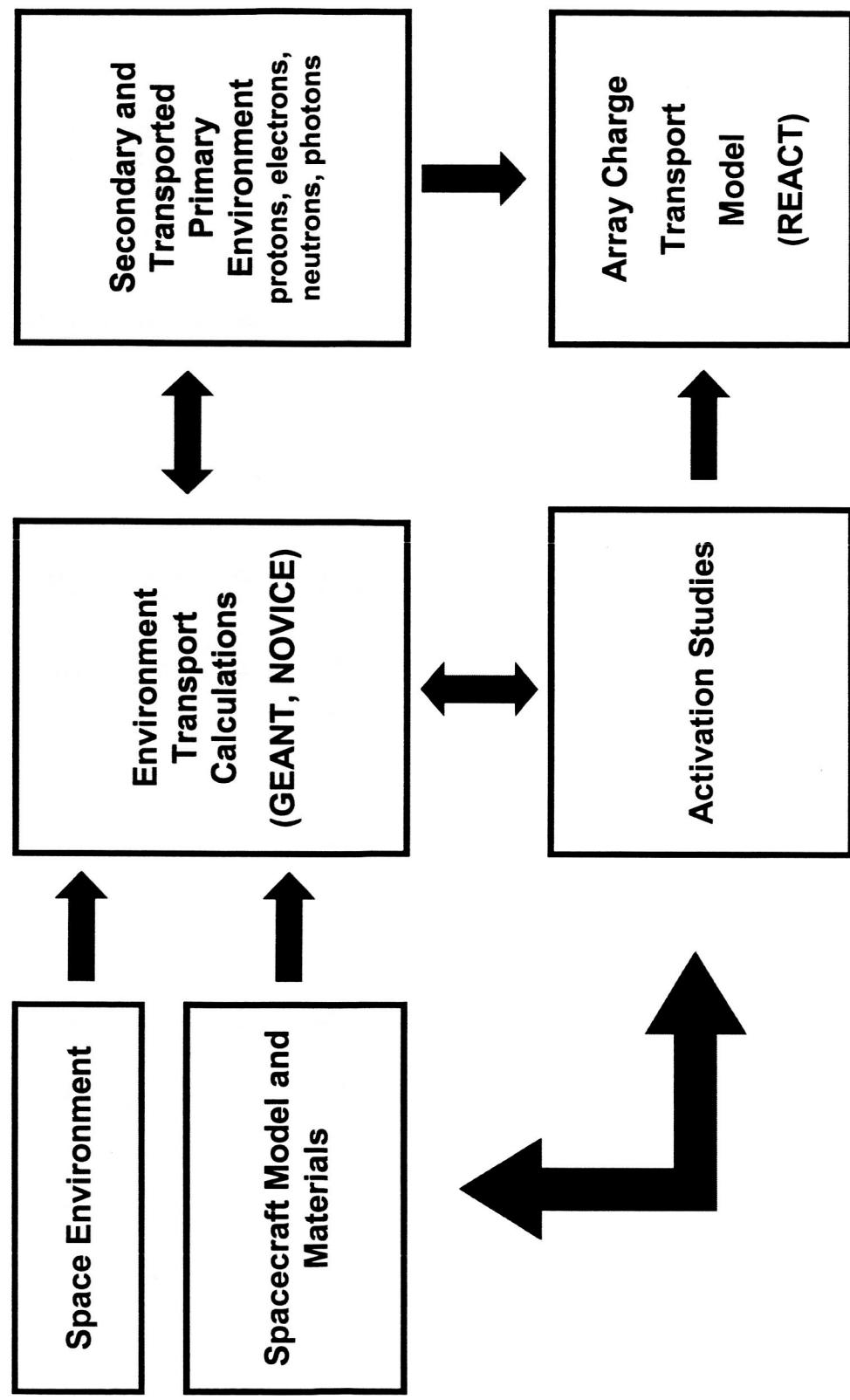
JWST IR Focal Plane Array Detectors

- REAG along with JWST team is currently working to assess radiation effects in HgCdTe Detector Arrays
 - Radiation induced transient (Prompt Response)
 - Low noise requirement: 3-10 electrons for 1000 sec integration time
 - Permanent degradation (TID and Displacement Damage)
 - Requirement of >90% good pixel at end of mission

FPA Transient Response Model

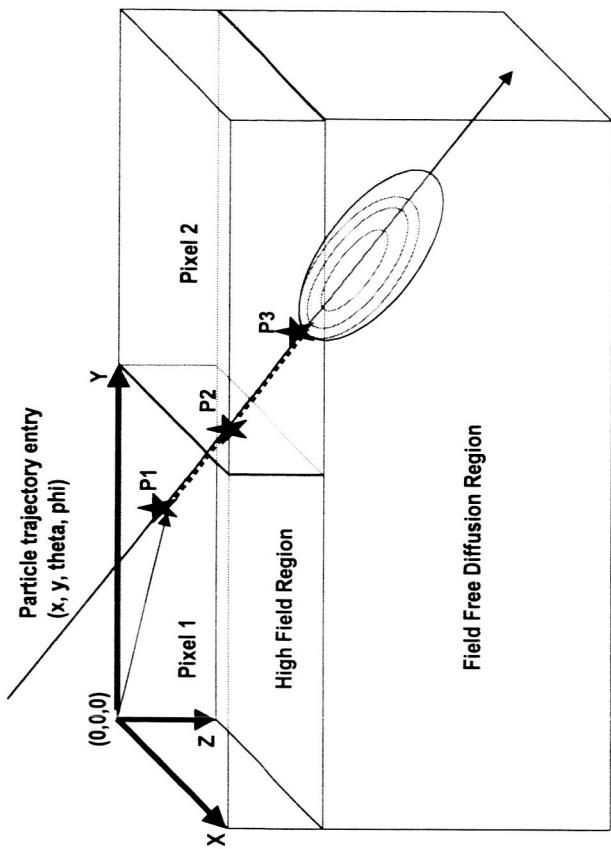
- Goal of analysis is to predict FPA response to incident energetic particles (protons, heavy ions, electrons)
 - Pixel-by-pixel charge contamination from particle hit
 - Quantify crosstalk and multi-pixel hits
- Source term is external radiation environment and transport through material surrounding FPA
 - Includes primary and secondary environment
 - Includes decay of activated material and inherent radioactivity
- Use detailed FPA charge collection model (REACT) to allocate charge to each pixel
- Output is simulation of FPA operation in JWST particle environment (e.g., FITS file)

General Modeling Approach



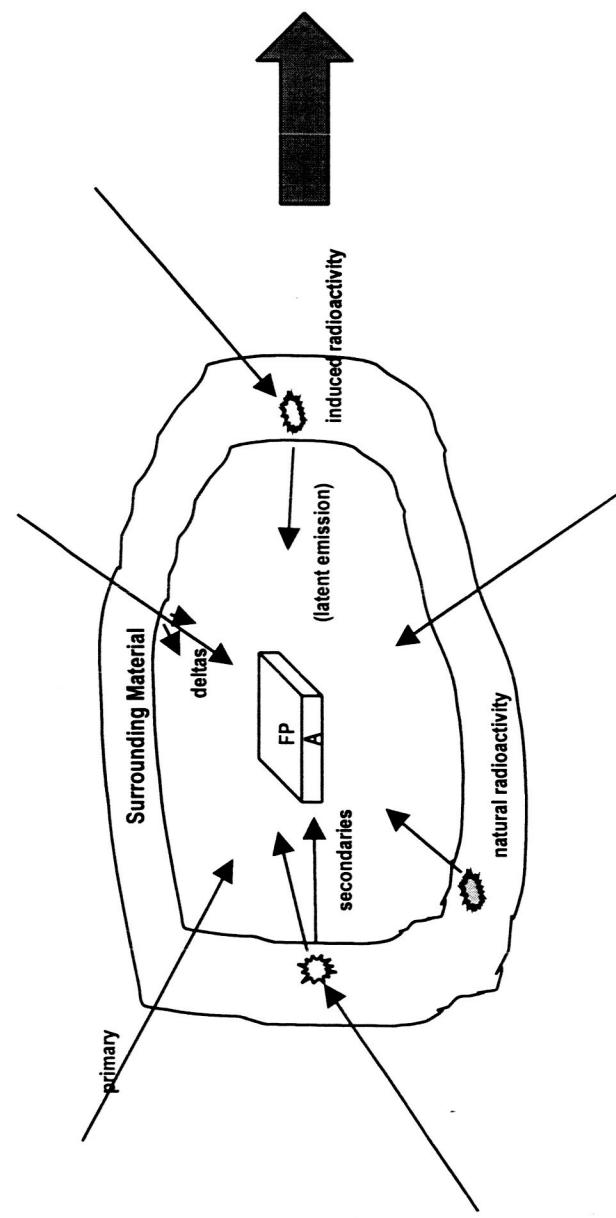
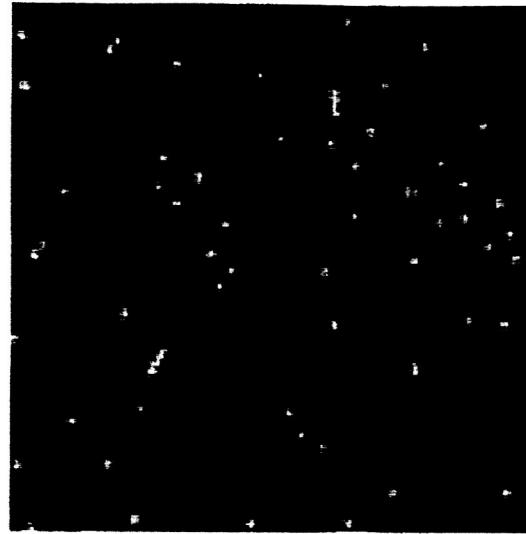
Array Charge Collection Model (REACT)

- Initial line source of minority carrier distribution based on particle LET and trajectory
- Drift and diffusion charge collection models applied depending on particle location
- Charge carrier history ends when either collected or recombined
- Charge distributed to pixels across array in accordance with drift and diffusion
- Output is pulse height distributions, crosstalk characterization, FITS files, etc.



Future Direction for Modeling on On-Orbit Prompt Response

- Predict the environment at the FPA using GEANT4, MCNPX, NOVICE, and EASY
 - Requires detailed information about the spacecraft structure around the FPA
- Determine the response of the FPA using REACT



Roadmap

- Collaborators:
 - NASA/GSFC
 - Vanderbilt University
- Also coordinating with *ESA* efforts
- Near Term Goals
 - Compare **GEANT4** results to other models
 - Ion track structure in Silicon
 - Proton-reaction recoil nuclei distributions
 - Develop **CRTTIP** techniques to be capable of predicting heavy ion and proton SEE rates using existing models
 - Convert *NASA*'s drift and diffusion modeling routines (called **REACT**) to be compatible with OOP
 - Proof of concept for establishing a parallel processing in **Geant4**
 - Vanderbilt has access to >120 node Cluster of >2GHz machines
 - Develop collaboration with **Geant4** development team

Roadmap: Intermediate and Long Term Goals

- **Intermediate Goals**
 - Develop Geant4 routine capable of predicting SEE's using REACT
 - Develop user define modules for using Geant4/REACT for SEE's in fiber link / optocoupler and benchmark against available radiation test data
 - This module will be available to the public in a user-friendly format
 - Develop full parallel processing capability for Geant4
- **Long Range Goals**
 - Development of user define Geant4/REACT modules for other technologies
 - SOI/SOS
 - SiGe and others
 - Develop capability of using Geant4 with Detailed Device Physics simulation for predicting circuit response
 - Continue to develop user define modules for using Geant4/REACT Making them available to the public in a user-friendly format

Computational Physics for Space Flight Applications

Presented by:

Robert A. Reed

NASA/GSFC Code 561
Greenbelt MD, 20771
robert.reed@nasa.gov

Supported in Part by:

- NASA Electronics Parts and Packaging (NEPP) Program
- Defense Threat Reduction Agency (DTRA)
- NASA Space Environment and Effects (SEE) Program
- NASA's James Webb Space Telescope (JWST)

Outline

- **Introduction to space radiation effects in microelectronics**
- **Using applied physics to help NASA meet mission objectives**
- **Example of applied computational physics**
 - James Webb Space Telescope
 - Single Event Effects in emerging microelectronic technologies
- **Future directions in applied computation physics**

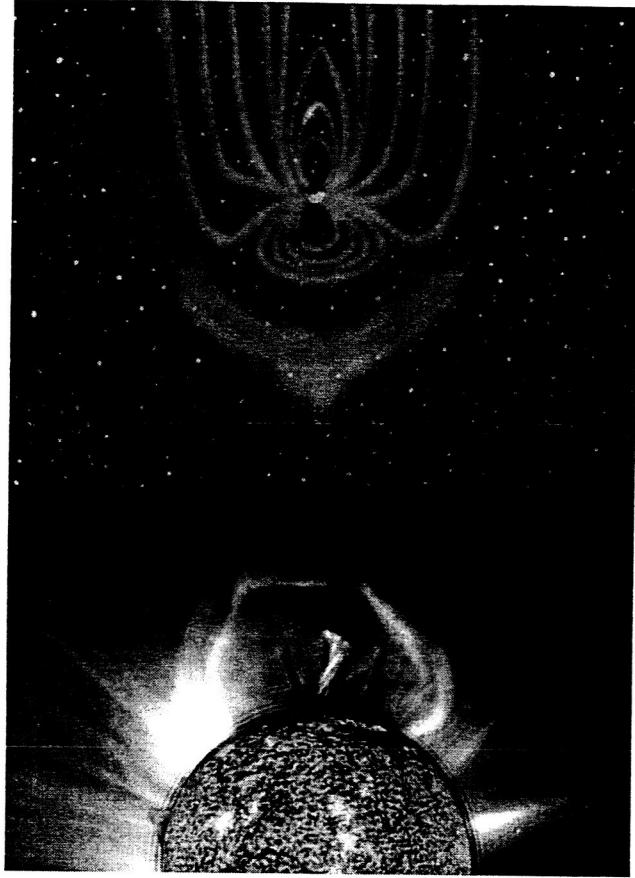
Space Radiation Environment

Three portions of the natural space environment contribute to the space environment effects hazard

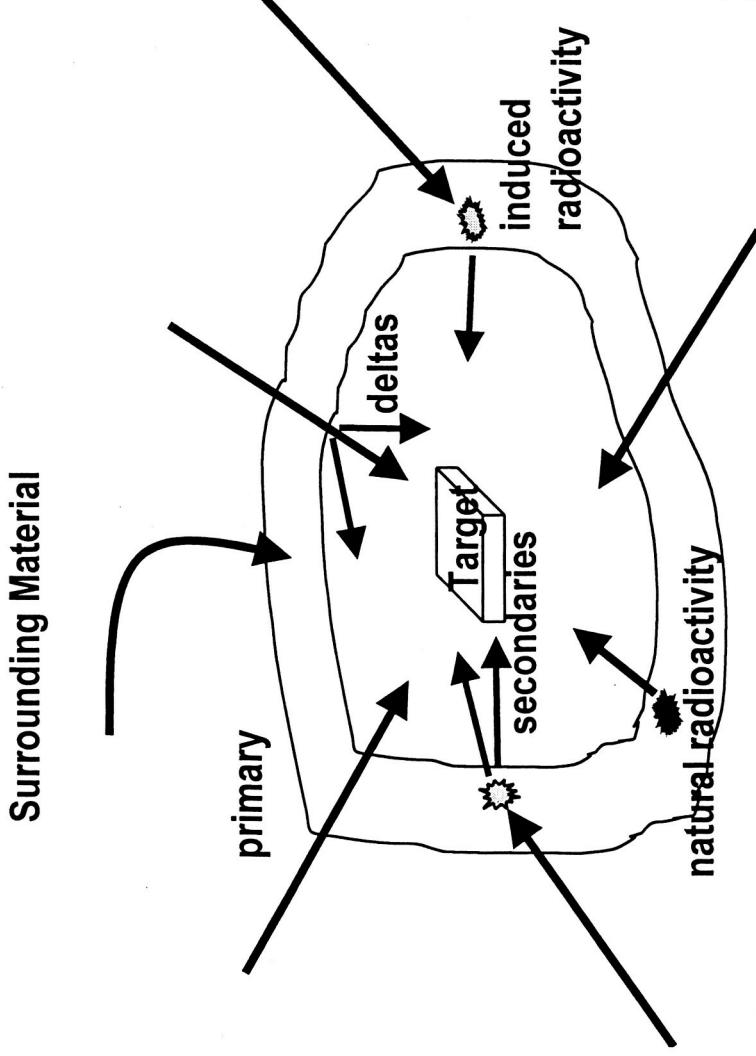
- Solar particles
 - Protons and heavier ions
- Galactic Cosmic Rays (GCR)
 - For earth-orbiting craft, the earth's magnetic field provide some protection for GCR
- Trapped particles (in the belts)

- Hazard observed is a function of orbit and timeframe

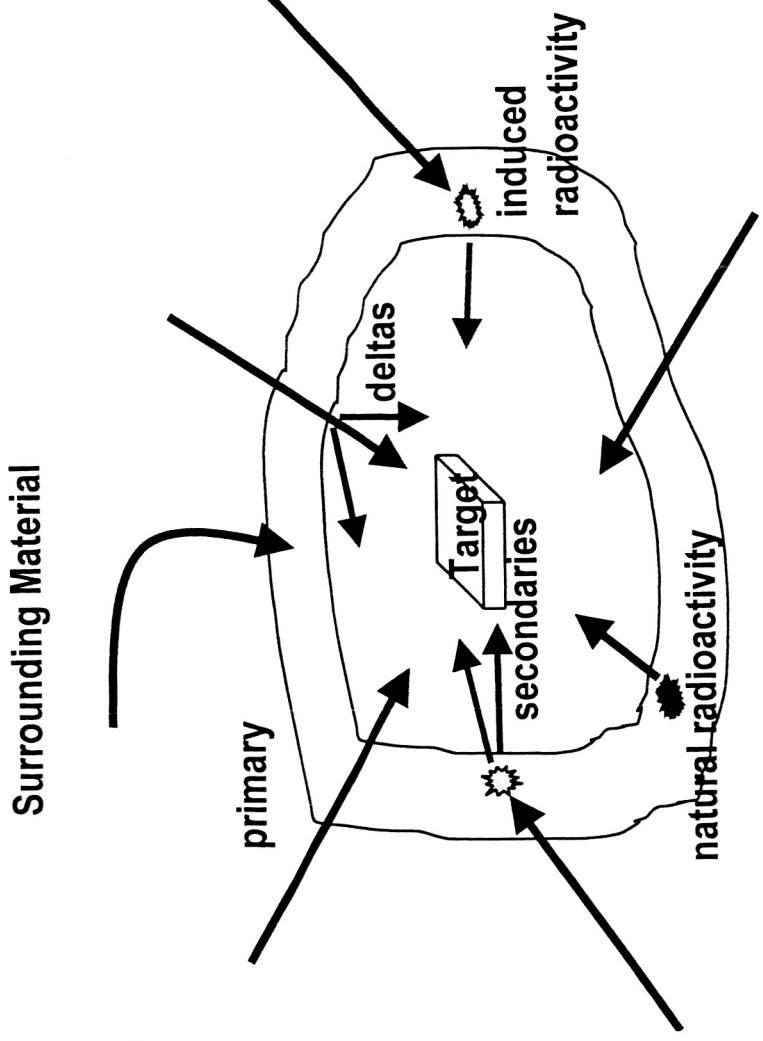
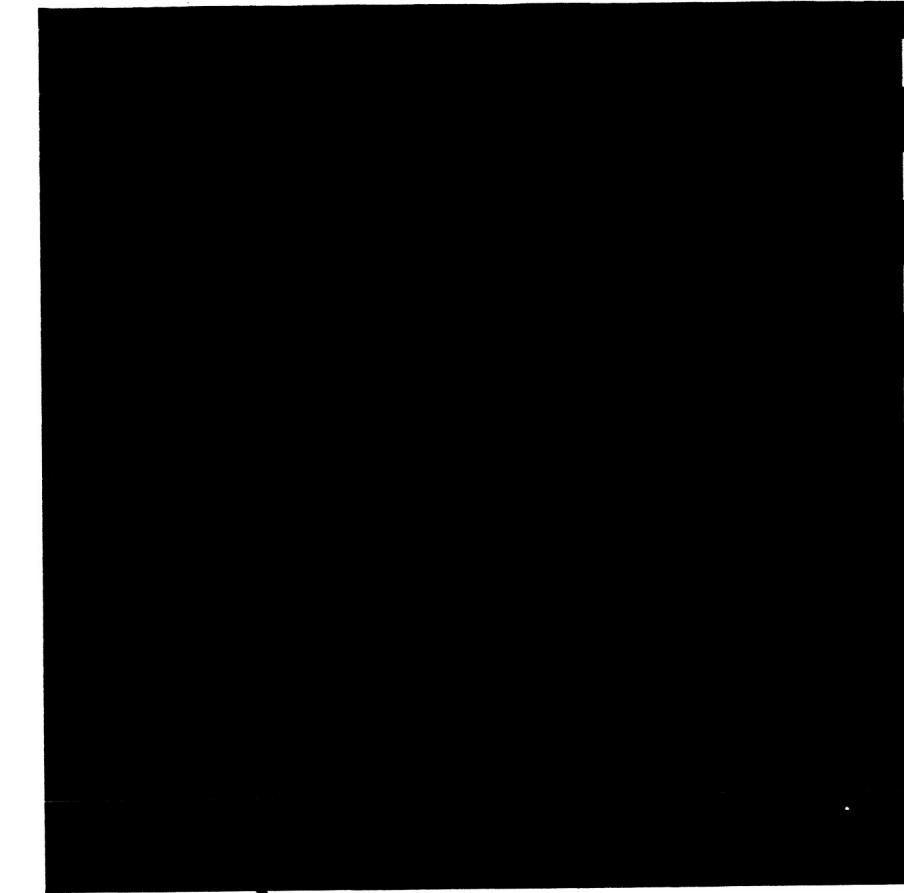
- Environment is dynamic. models are static



Modeling the Interaction of the Space Radiation Environment with the Spacecraft and Targets



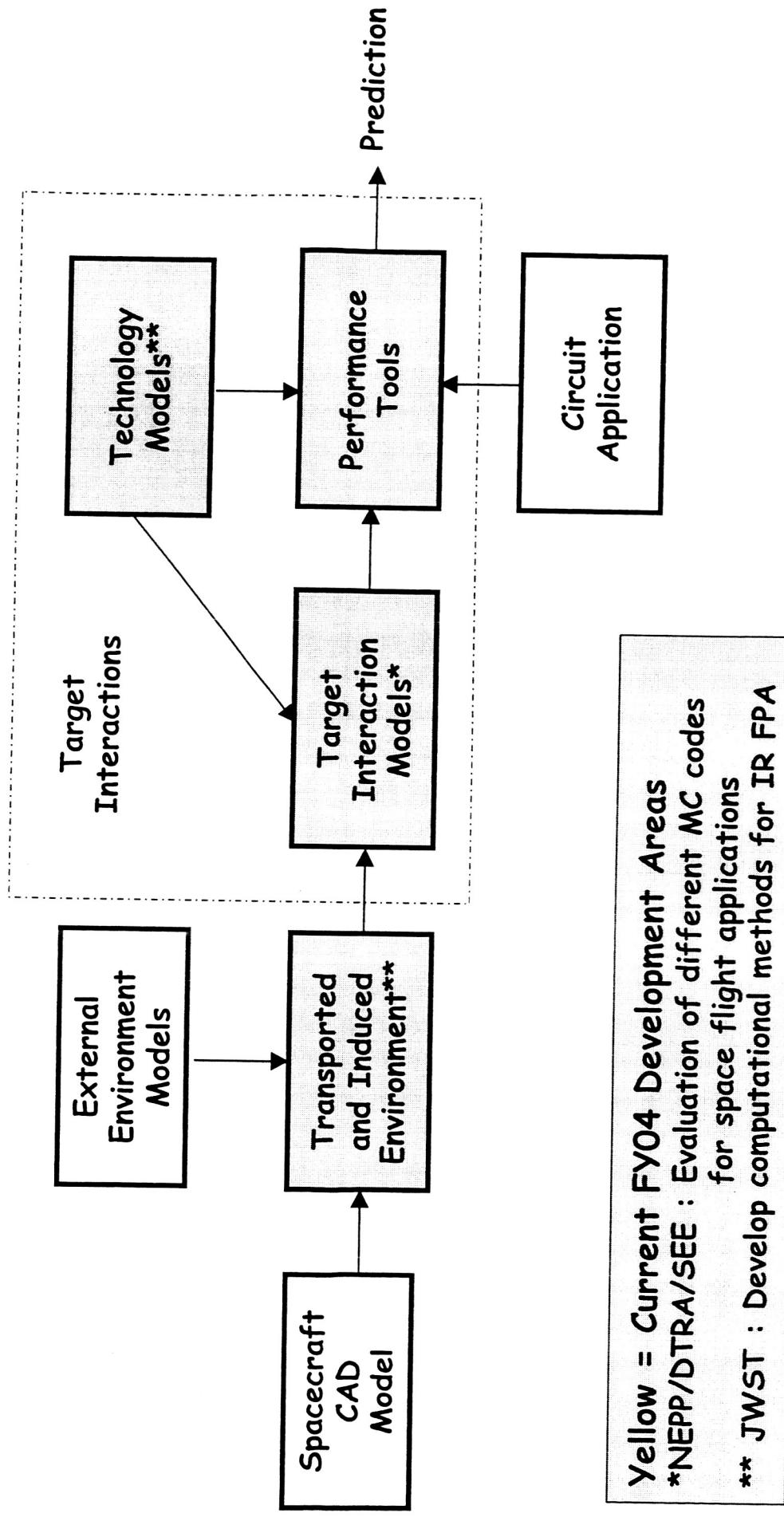
Modeling the Interaction of the Space Radiation Environment with the Spacecraft and Targets



Monte Carlo Based Computation Physics Tools Currently Used at NASA/GSFC

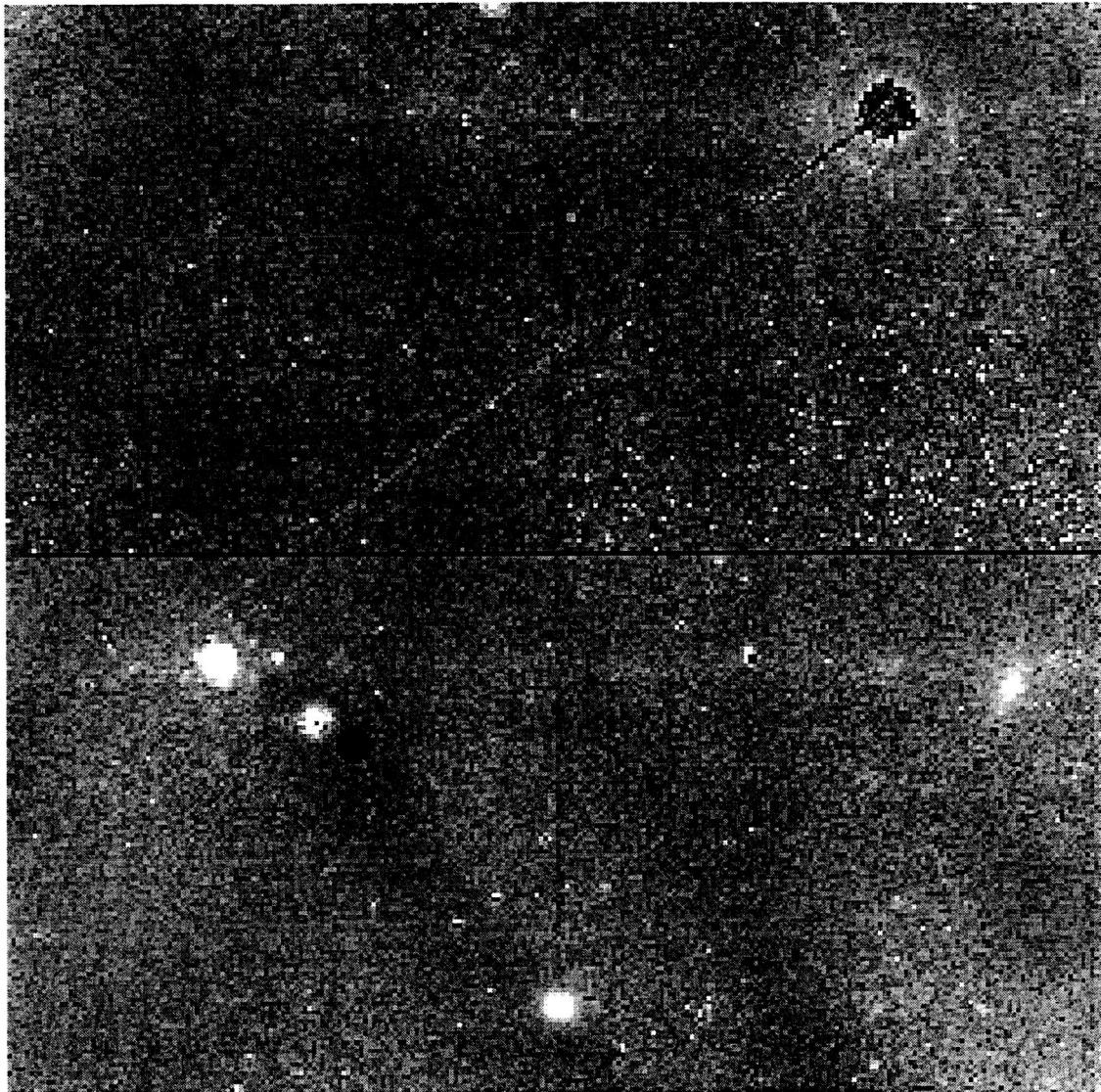
- *GEANT4*
 - A multi-national team of physicists and engineers are developing *Geant4* for the express purpose to Monte Carlo simulation of the passage of particles through matter.
 - Its application areas include high-energy physics and nuclear experiments, medical, accelerator and space physics studies.
 - *EMPC Inc.'s* (a private company) *NOVICE* code suite
 - Developed to be a user-friendly, engineering tool for use, in part, by the space radiation effects community.
 - Its developer is highly regarded as an expert in radiation transport by the space radiation effects community.
- The Los Alamos National Laboratory's *Monte Carlo N-Particle extended (MCNPX)*
 - A general-purpose computer code that can be used for particle transport through materials.
 - Its application areas are similar to *Geant4*.
- *NASA's Radiation Effects Array Charge Transport (REACT)*
 - Simulation of charge transport through a semiconductor
 - Quasi-device physics (QDep) code
- *Clemson University Proton Interaction in Devices (CUPID)*
 - Simulation of proton spallation reactions in Silicon
 - Tracks energy deposited in a right Rectangular Parallelepiped (RPP) volume

Space Computational Radiation Interaction Performance Tools (SCRIPT)



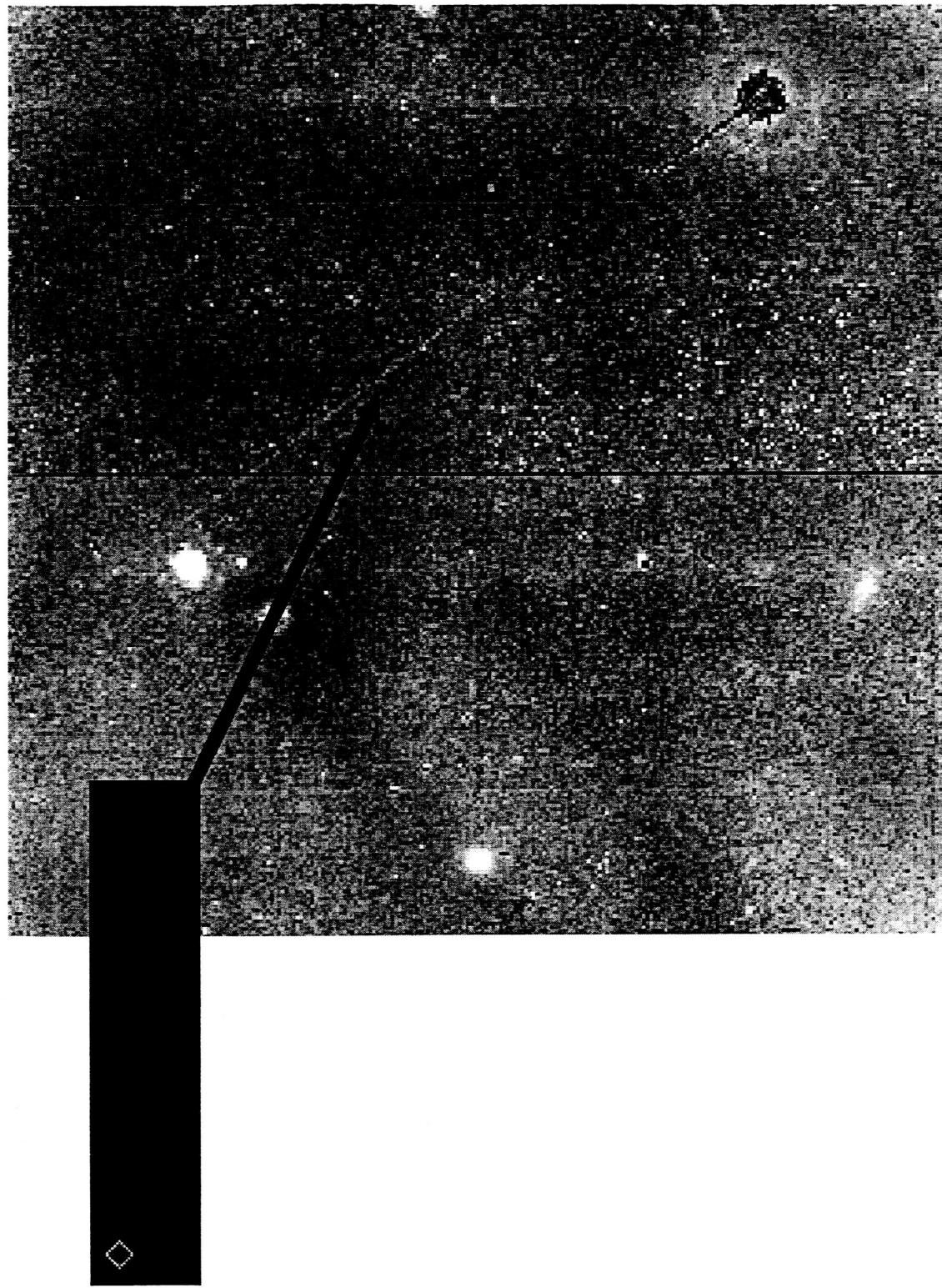
Space Radiation Interactions as Observed by NICMOS

Figure 2.4



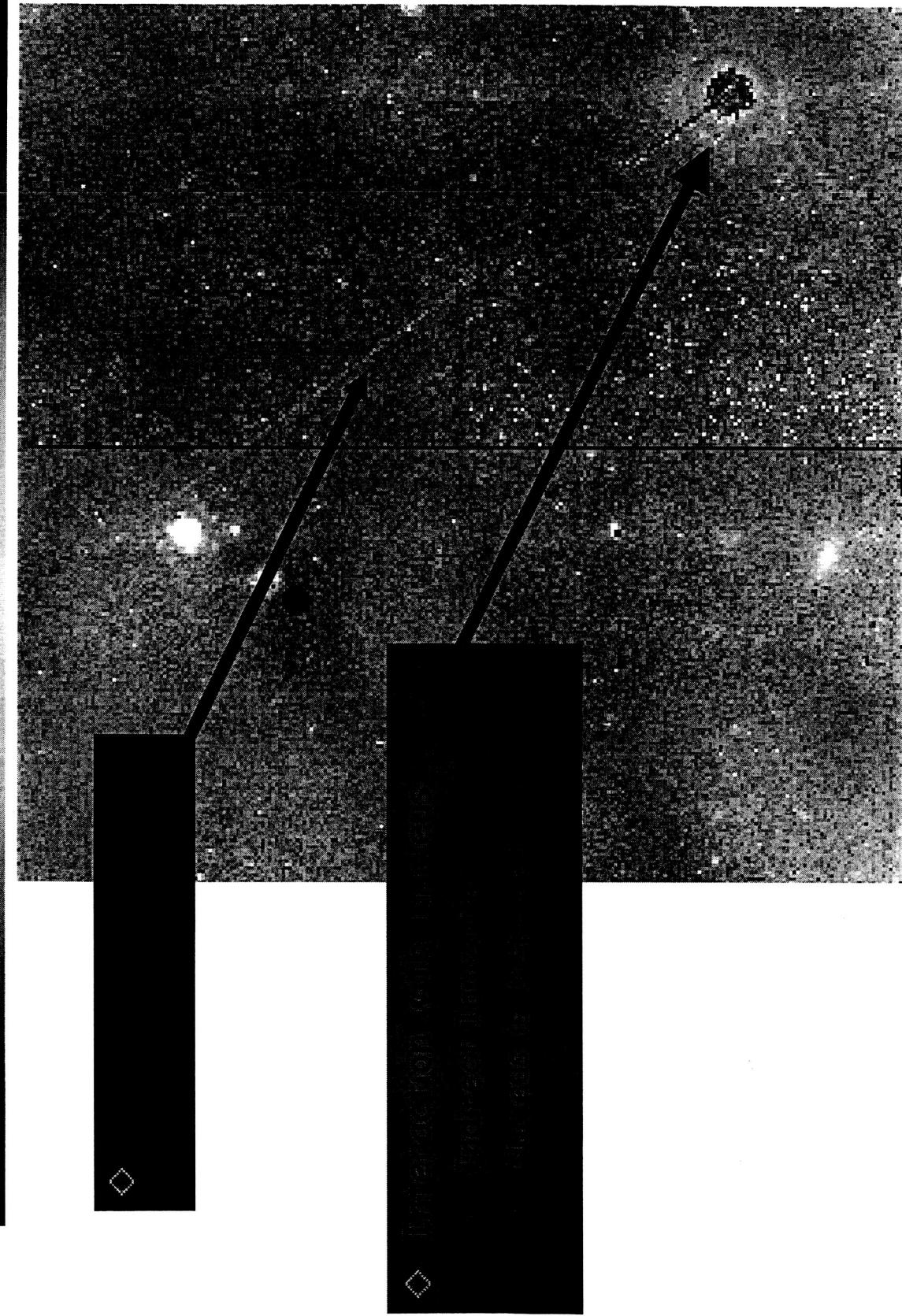
Space Radiation Interactions as Observed by NICMOS

Figure 2.4



Space Radiation Interactions as Observed by NICMOS

Figure 2.4



Prompt Ionizing Events

Figure 2.4

Single Event Effects (SEE)

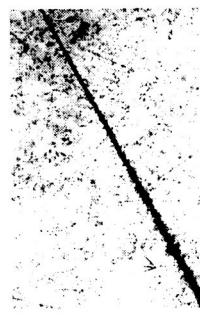
Prompt Ionizing Events

Figure 2.4

Single Event Effects (SEE)

- Direct Ionization

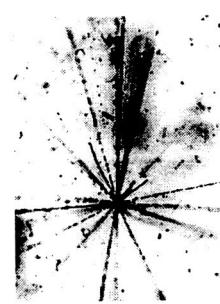
- Typically Heavier Ions ($Z>1$)
- Linear Energy Transfer (LET)
 - . Energy per length
- Frequency of the Events in space radiation



Direct

- Indirect Ionization

- Fragments from Nuclear Collision
- Proton Energy
- Frequency of the Events in space radiation



Indirect

P.J McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course

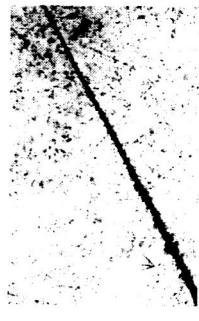
Prompt Ionizing Events

Figure 2.4

Single Event Effects (SEE)

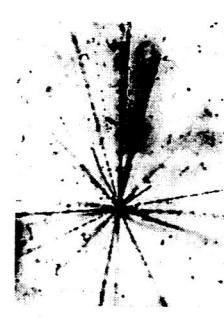
Direct Ionization

- Typically Heavier Ions ($Z > 1$)
- Linear Energy Transfer (LET)
 - Energy per length
- Frequency of the Events in space radiation



Indirect Ionization

- Fragments from Nuclear Collision
- Proton Energy
- Frequency of the Events in space radiation



Direct

Charge collected on a sensitive node in an electrical circuit causing an unwanted change in information stored on the component

- Single Event Upset
- Single Event Latchup
- Single Event Transient
- Single Event Gate Rupture
- Single Event Functional Interrupt
- Single Event ...

Indirect

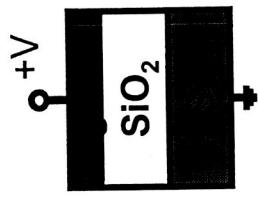
P.J McNulty, Notes from 1990 IEEE Nuclear and Space Radiation Effects Conference Short Course

Cumulative Degradation for Multiple Ionizing Events

Figure 2.5

Total Ionizing Dose (TID)

BEFORE IRRADIATION



- Permanent damage, some annealing occurs for certain devices
- Can lead to Functional failure

DURING IRRADIATION

DURING AND AFTER IRRADIATION



IONIZATION AND RECOMBINATION

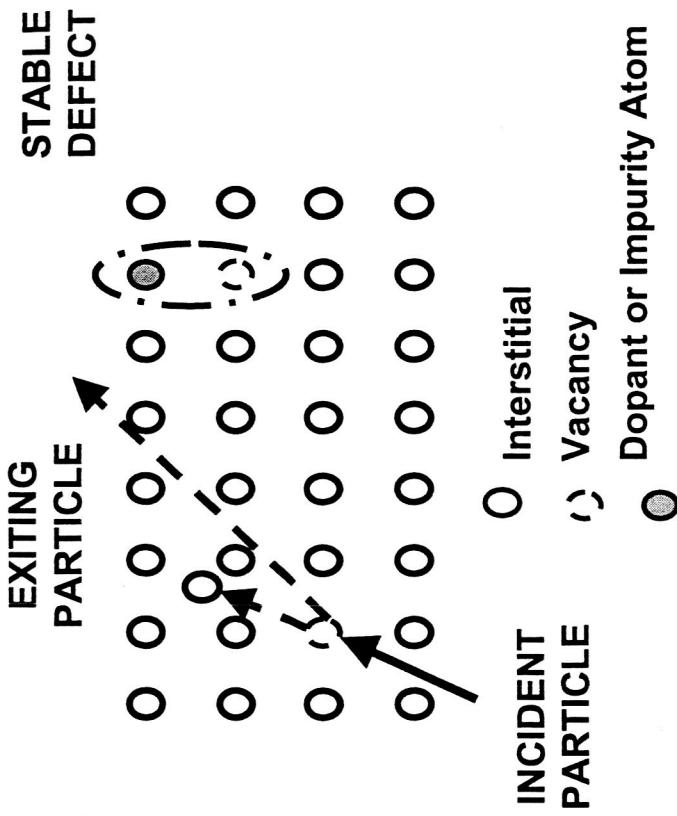
DRIFT, DIFFUSION AND TRAPPING

J.L. Leray, Notes from 1999 IEEE Nuclear and Space Radiation Effects Conference Short Course

Cumulative Degradation and Prompt Response for Non-Ionizing Events

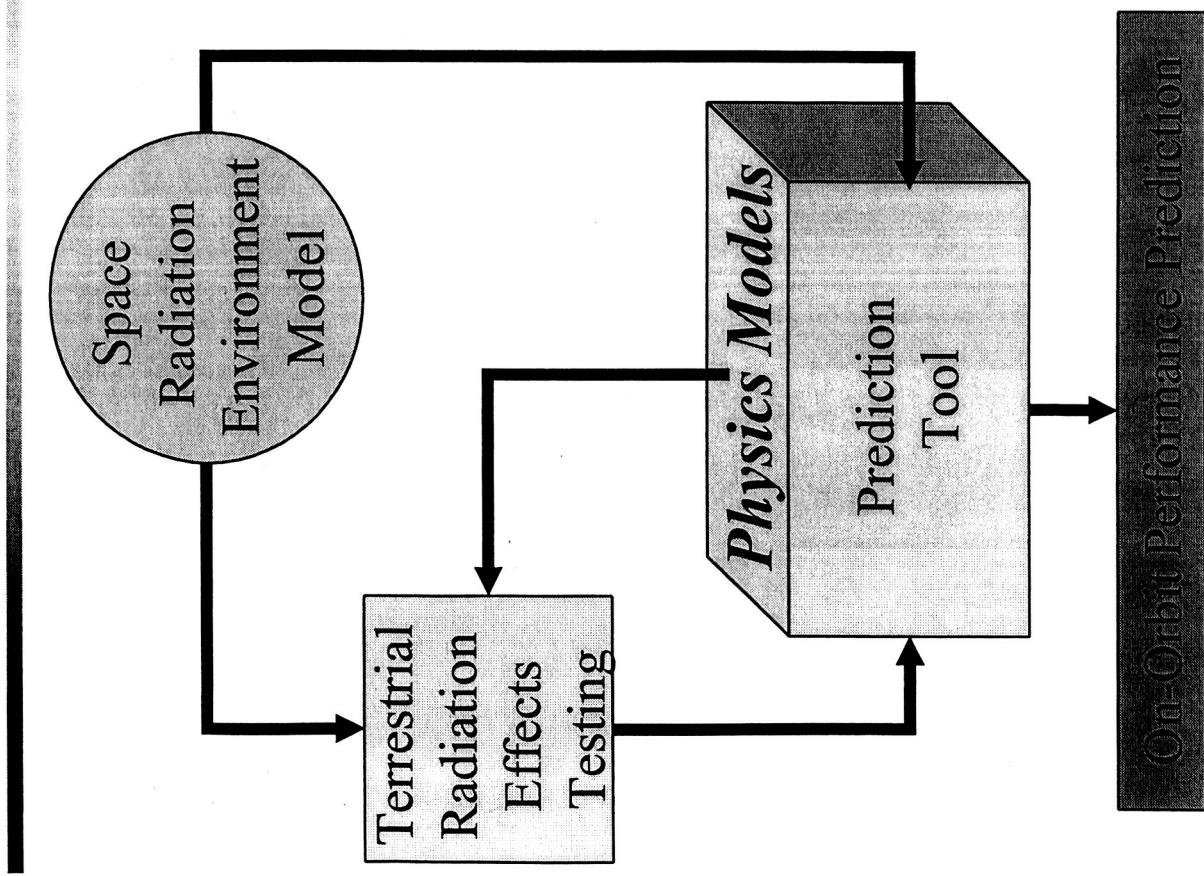
Displacement Damage

- Cumulative effects that cause device performance degradation
 - Displacement Damage Dose
- Prompt effects causing device performance degradation
- Permanent damage, some annealing occurs for certain devices



P.W. Marshall and C.J. Marshall, Notes from 1999 IEEE Nuclear and Space Radiation Effects Conference Short Course

General On-Orbit Performance Prediction

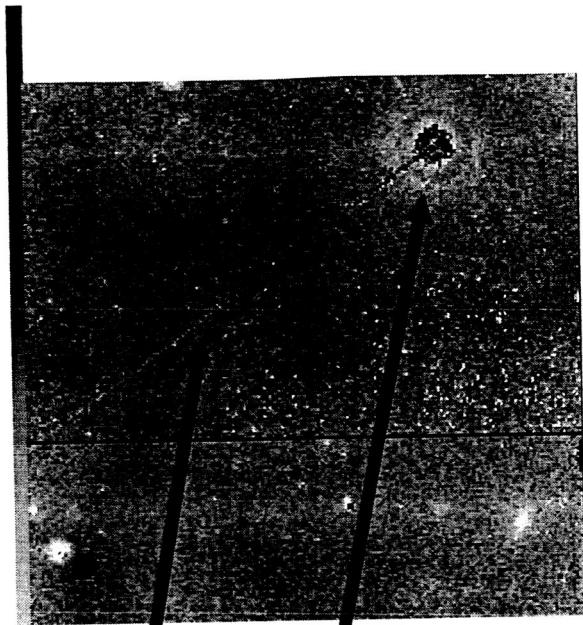


- The details of each step in this process depend on the type effect that is being analyzed
 - e.g. prompt response (SEE) will be different than cumulative degradation (TID)

Applications of Computation Physics

Figure 2.4

- **Atomic Interactions**
 - Direct Ionization
 - TID
 - SEE
- **Interaction with Nucleus**
 - Indirect Ionization
 - Nucleus is Displaced
 - SEE
 - Displacement Damage



Computational Radiation Transport and Interaction Physics (CRTIP)

- **NOVICE** is the best suited for TID studies*
 - Adjoint mode monte-carlo
- **MCNPX** is the best suited for displacement damage studies*
 - Uses Lindhard energy partitioning
 - Includes elastic scattering
- **GEANT4** is the suited for SEE studies*
 - Most flexible for user modules
- **REACT** is the suited for SEE studies*
 - Quasi-device physics code

* These results will change as we review other codes and as these codes improve



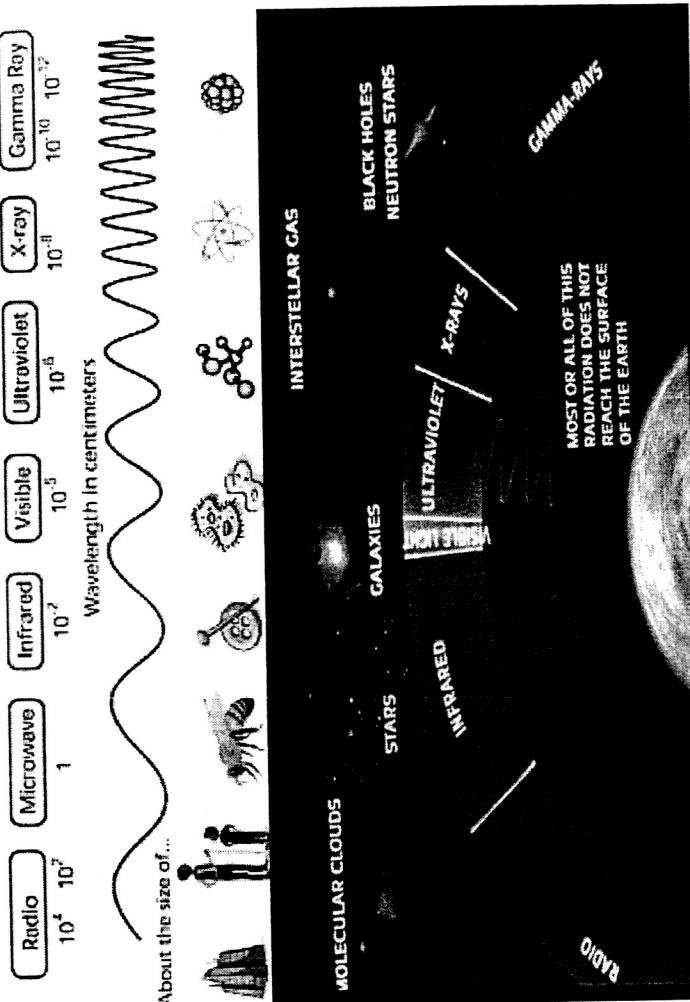


Computational Radiation Transport and Interaction Physics

James Webb Space Telescope

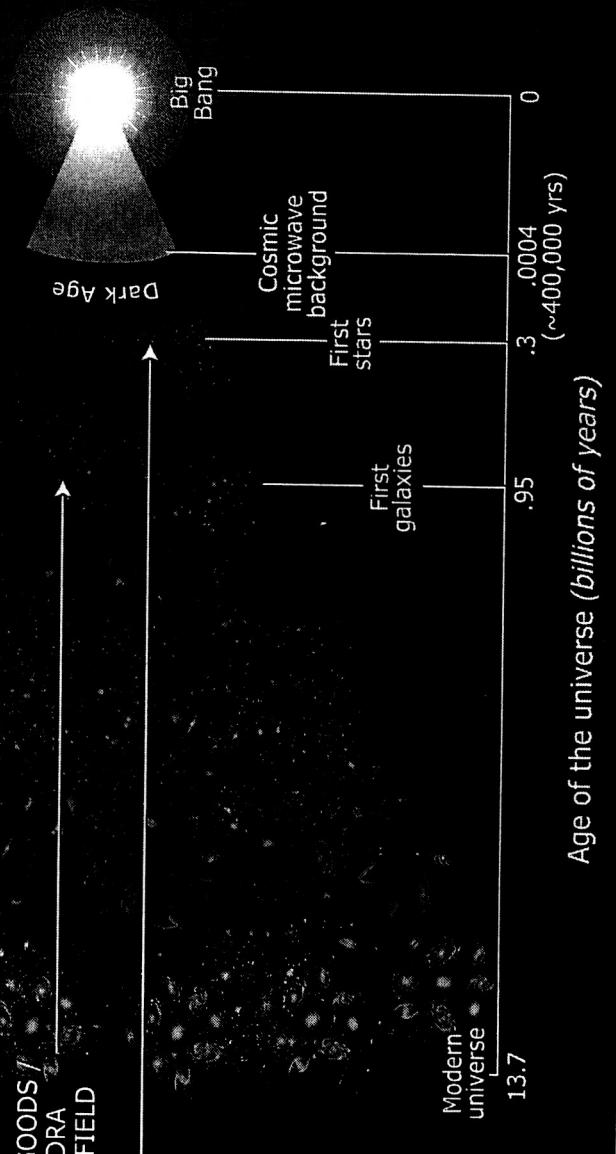
Low Noise Quantitative Detection Across the Spectrum

- **Ground-based Radio Astronomy**
- **Microwave looks at the Cosmic Microwave Background**
 - COBE, FIRS, WMAP
- **Mid to long wave IR (>5 mm)**
 - SIRTF, JWST
- **Near Infrared**
 - HST - WFC3 & NICMOS
- **Visible (panchromatic)**
 - HST - WFC2, ACS, WFC3
- **Near uV to VUV (solar phys)**
 - SOHO, SDO, STEREO
- **X-ray**
 - CHANDRA, XMM-Newton
- **γ -ray**
 - GRO, GLAST, RHESSI
- **Gravity wave - Laser Interferometer Space Antenna - LISA**

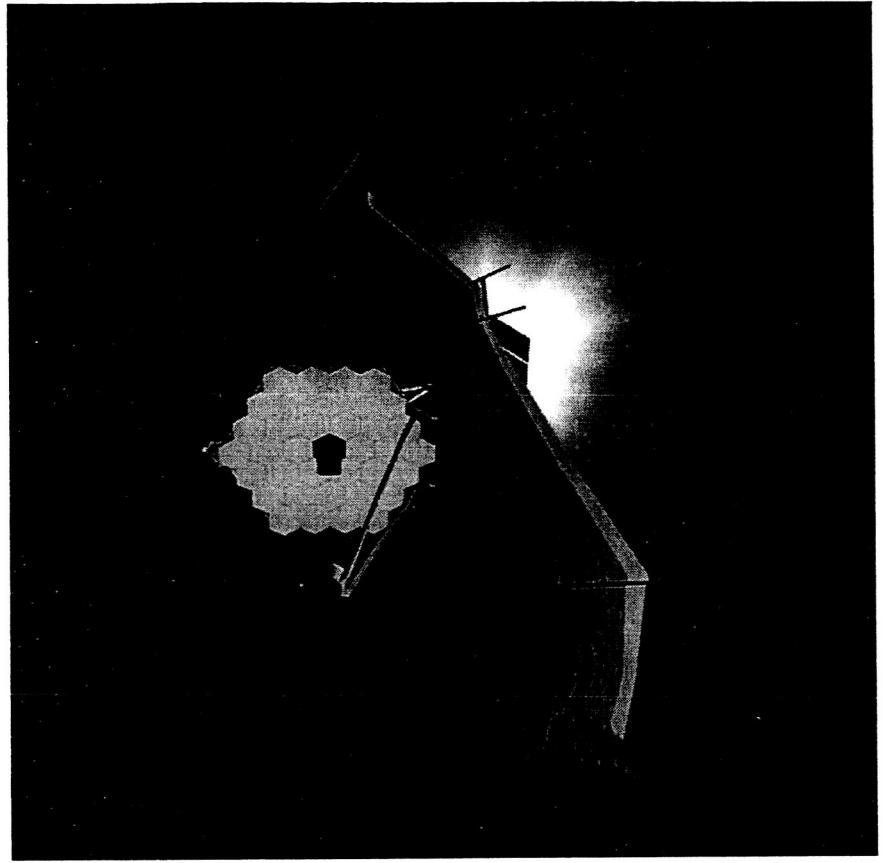
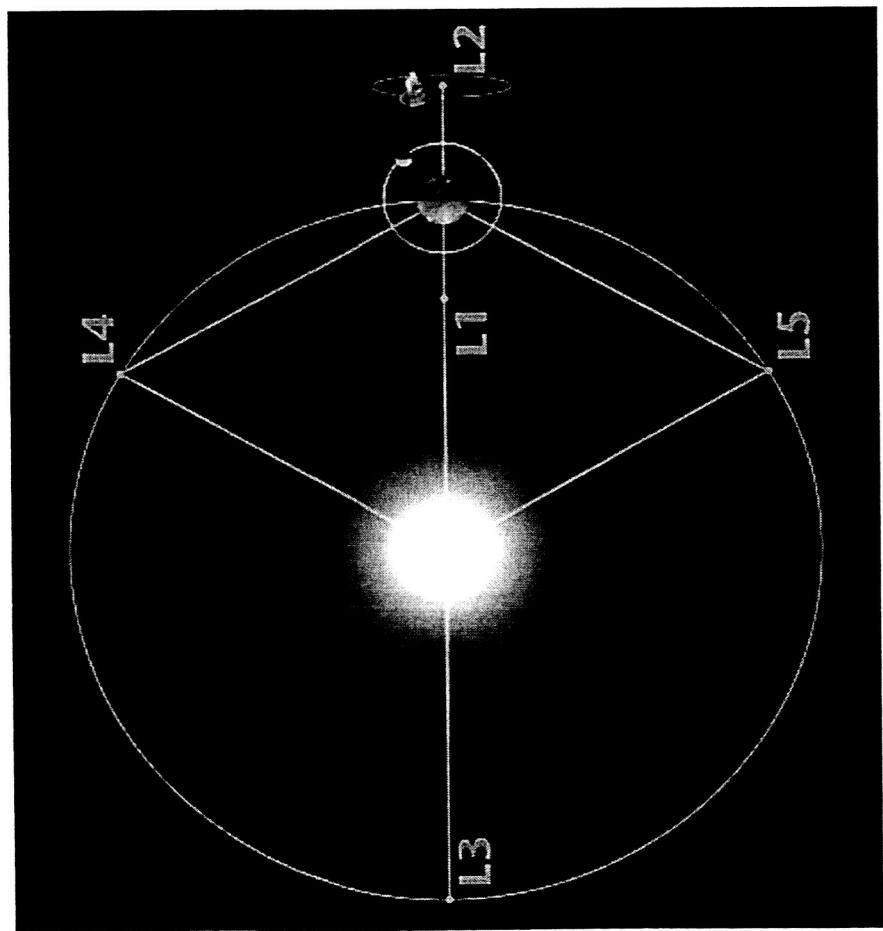


James Webb Space Telescope

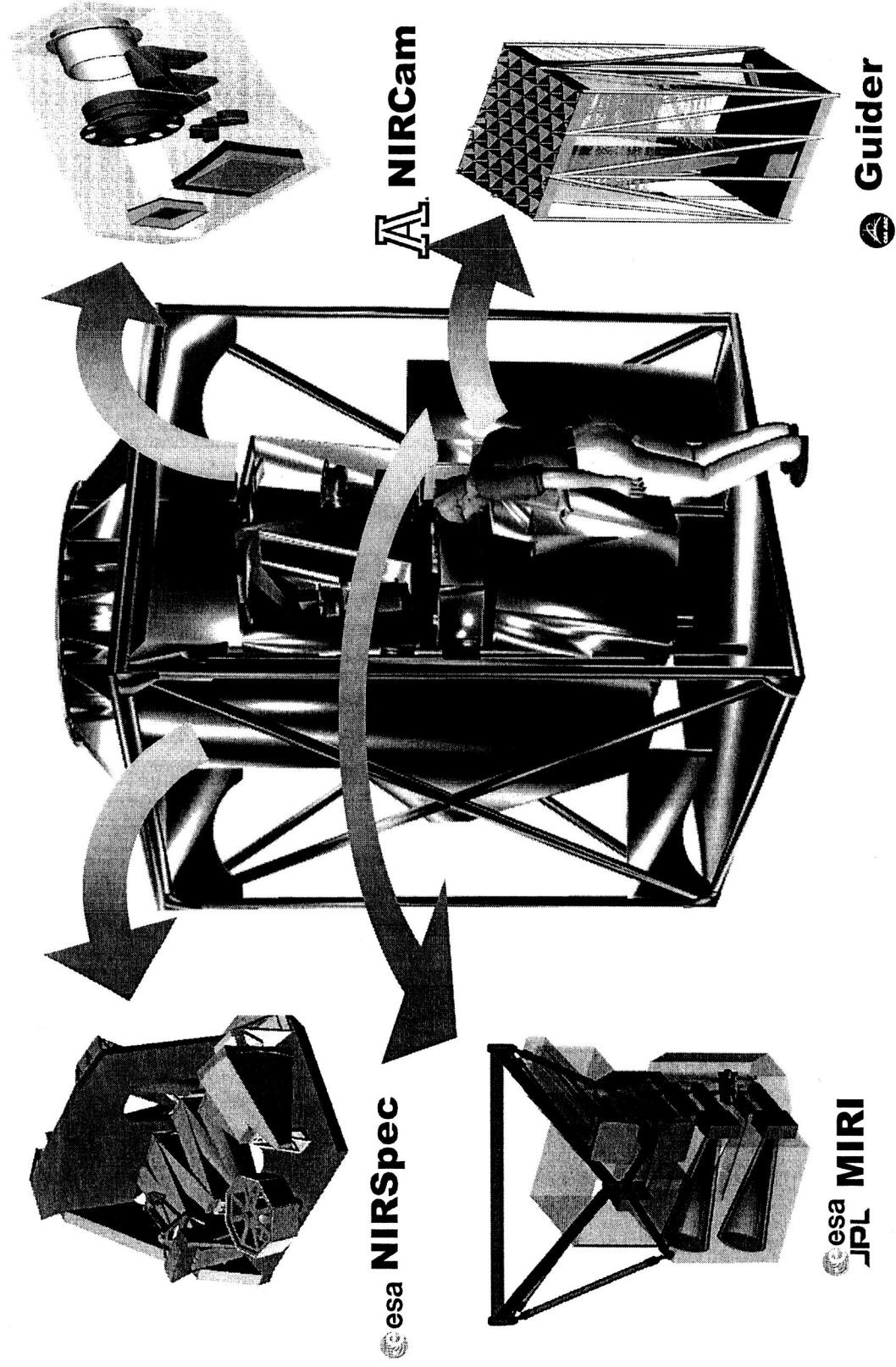
Seeing back into the cosmos



James Webb Space Telescope



James Webb Space Telescope



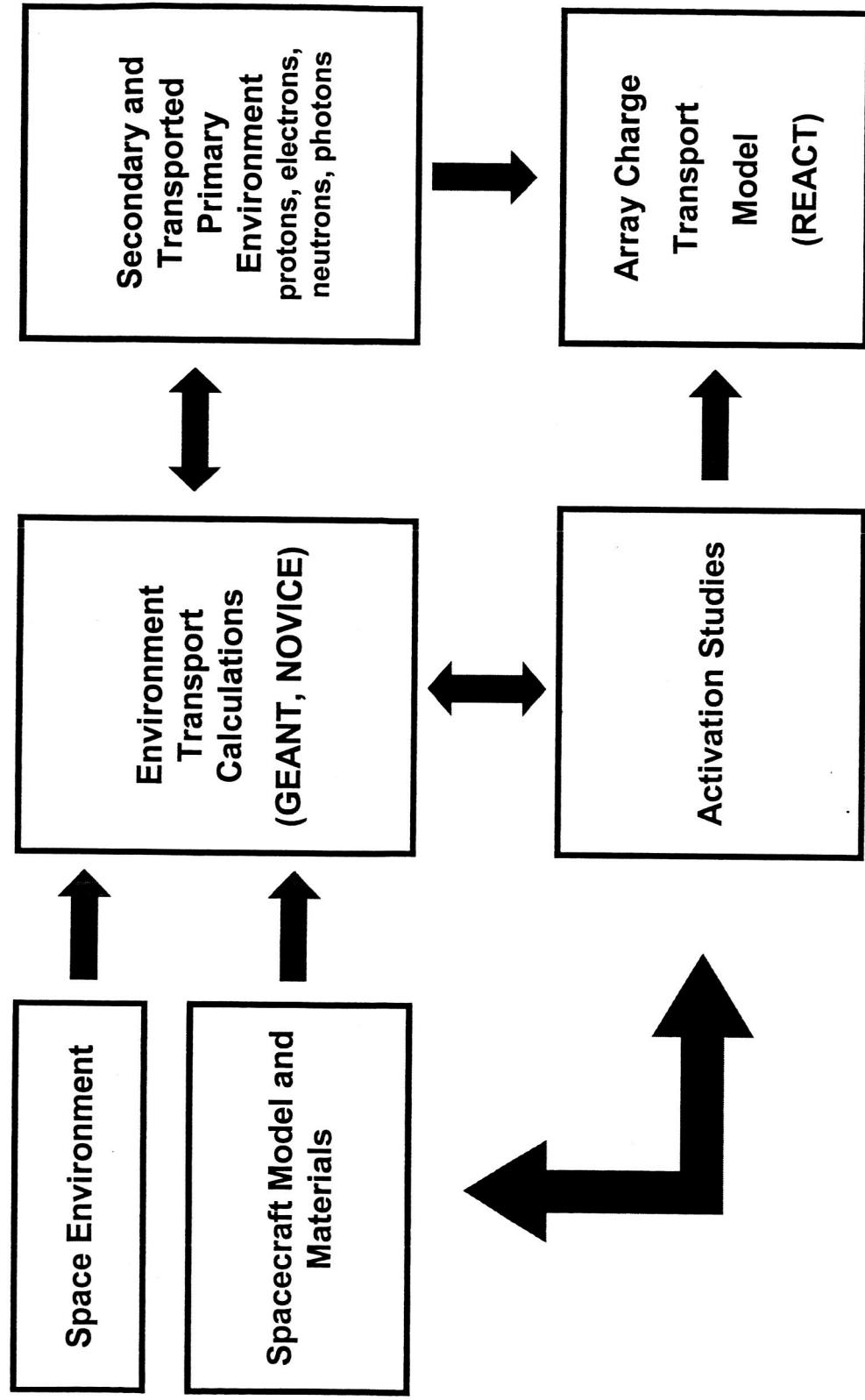
JWST IR Focal Plane Array Detectors

- REAG along with JWST team is currently working to assess radiation effects in HgCdTe Detector Arrays
 - Radiation induced transient (Prompt Response)
 - Low noise requirement: 3-10 electrons for 1000 sec integration time
 - Permanent degradation (TID and Displacement Damage)
 - Requirement of >90% good pixel at end of mission

FPA Transient Response Model

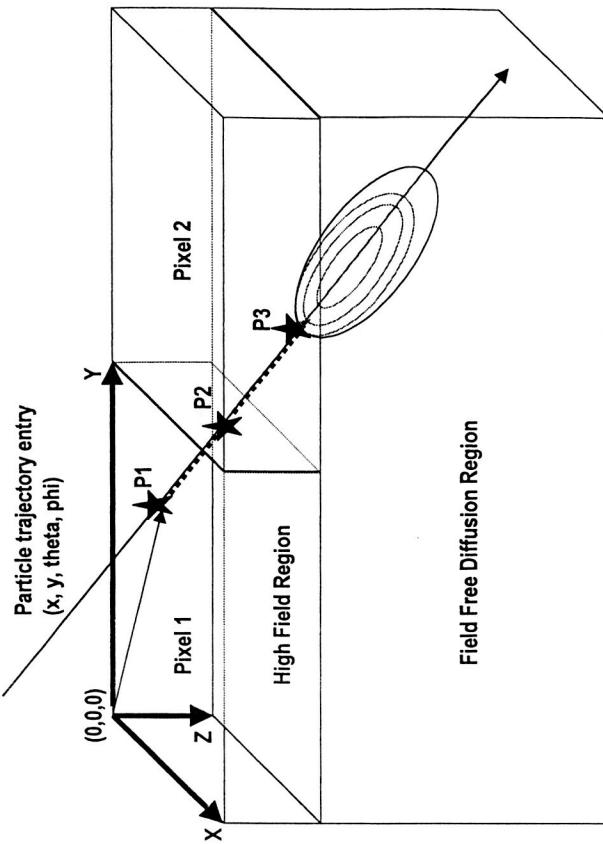
- Goal of analysis is to predict FPA response to incident energetic particles (protons, heavy ions, electrons)
 - Pixel-by-pixel charge contamination from particle hit
 - Quantify crosstalk and multi-pixel hits
- Source term is *external radiation environment* and *transport through material surrounding FPA*
 - Includes primary and secondary environment
 - Includes decay of activated material and inherent radioactivity
- Use detailed FPA charge collection model (REACT) to allocate charge to each pixel
- Output is simulation of FPA operation in JWST particle environment (e.g., FITS file)

General Modeling Approach



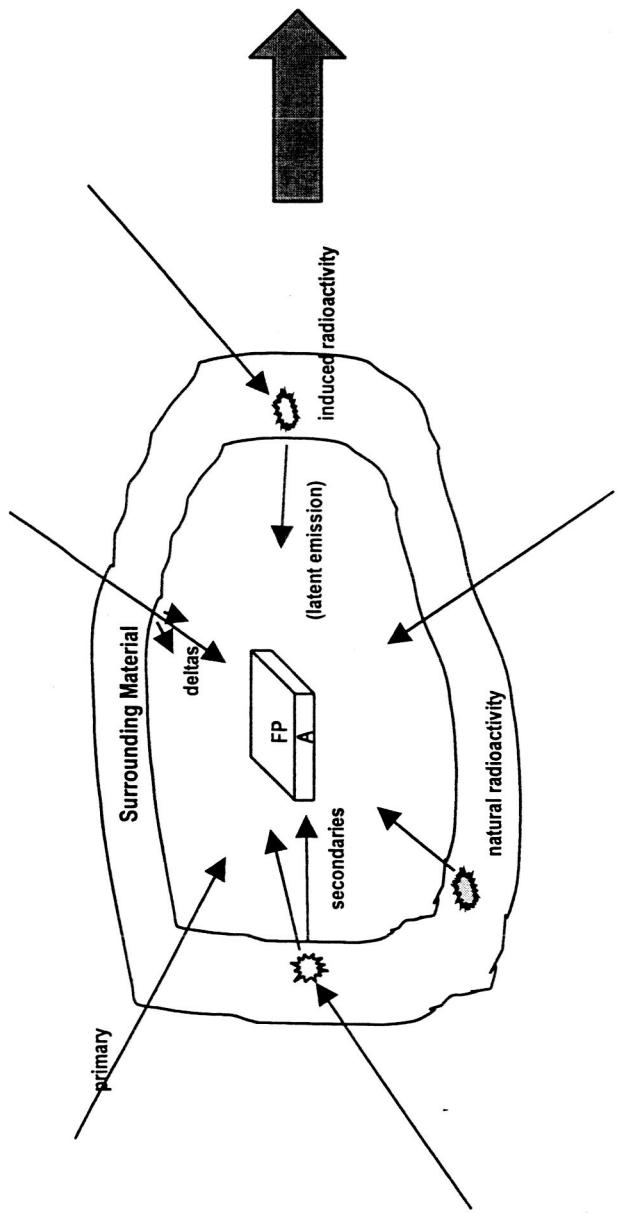
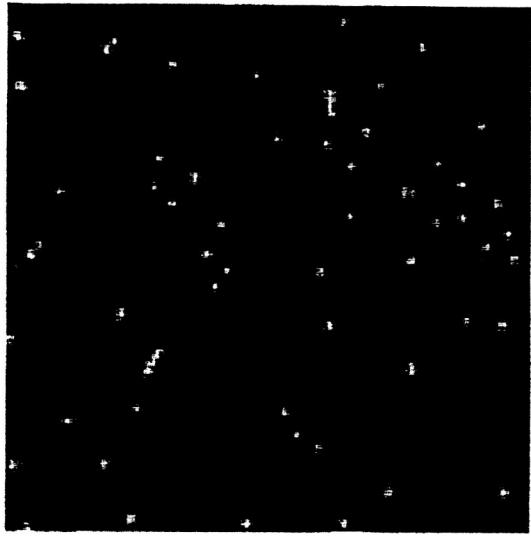
Array Charge Collection Model (REACT)

- Initial line source of minority carrier distribution based on particle LET and trajectory
- Drift and diffusion charge collection models applied depending on particle location
- Charge carrier history ends when either collected or recombined
- Charge distributed to pixels across array in accordance with drift and diffusion
- Output is pulse height distributions, crosstalk characterization, FITS files, etc.



Future Direction for Modeling on On-Orbit Prompt Response

- Predict the environment at the FPA using GEANT4, MCNPX, NOVICE, and EASY
 - Requires detailed information about the spacecraft structure around the FPA
- Determine the response of the FPA using REACT



Roadmap

- Collaborators:
 - NASA/GSFC
 - Vanderbilt University
- Also coordinating with *ESA* efforts
- Near Term Goals
 - Compare *GEANT4* results to other models
 - Ion track structure in Silicon
 - Proton-reaction recoil nuclei distributions
 - Develop CRTIP techniques to be capable of predicting heavy ion and proton SEE rates using existing models
 - Convert NASA's drift and diffusion modeling routines (called REACT) to be compatible with OOP
 - Proof of concept for establishing a parallel processing in *Geant4*
 - Vanderbilt has access to >120 node Cluster of >2GHz machines
 - Develop collaboration with *Geant4* development team